SOIL COMPACTION AND STAND GROWTH

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INTRODUCTION

There continues to be considerable interest in the effects of soil compaction on forest regeneration and the subsequent growth of trees and stands. The problem is complex because of the extent of soil compaction resulting from the use of equipment for harvesting, site preparation and regeneration depends on such factors as soil type, soil water content, soil organic carbon content, as well as the type of equipment and the number of passes made over a given location. Also, equipment use rarely produces a simple compaction effect similar to that obtained by the static loading of a soil. As well as compacting the soil, equipment use results in shearing effects, varying amounts of surface soil displacement, and soil mixing. When stands are partially harvested, deleterious effects of soil surface disturbance are confounded by the potential for increased growth through release and thinning. It is not surprising therefore that research on "compaction" has produced varied results.

Soil compaction and associated effects have been shown to modify physical, chemical, and biological properties of soils. These changes in the soil can have substantial effects on the growth of roots, seedlings, and trees. Extensive research in North America has provided broad documentation of the nature and extent of these effects. Much of the work, however, has been done in an agricultural context and has questionable direct relationship to forest conditions. More importantly, only a fraction of past research has addressed the problem of the effects of soil disturbance on tree growth; and no studies have adequately evaluated effects on stand growth.

Reviews of soil compaction have been made in the past and a repetition of this work will not be presented here. Perhaps the best recent review in terms of its relevance to California conditions is the 1978 Report on the Findings of the Soil Compaction Study Task Force, a 48-page document in the USDA Forest Service's 1979 solicitation for a study plan, on soil compaction (USDA, 1979).

Past studies have shown that the potential for forest operations to cause adverse effects on soils is high. Froehlich (1977) concluded that under tractor logging 20 to 40 per cent of the area may be covered by skid trails and that site quality of the average skid trail is reduced one site class below adjacent areas. Compaction tends to increase survival of natural regeneration, but growth of seedlings and individual trees is reported to be reduced by 10-20 percent to as much as 60 percent. The wide range in growth reduction reported reflects differences in tree age, degree of compaction, soil type, and accompanying disturbance of the soil surface. It should be noted, however, that under certain conditions of soil type, soil moisture, and type of equipment operations, no reduction in tree growth has been measured.

The bulk of literature on the subject indicates that soil compaction and associated soil disturbance is likely to cause some reduction in growth of individual trees. The problem confronting forest managers, however, is the extent to which compaction affects the growth of stands. No studies have directly addressed this issue. All past attempts to evaluate effects on stand growth have been made by evaluating the performance of individual trees and then projecting this reduction across the area of operation. Table 1 summarizes the growth reductions

TABLE 1: Comparison from the literature of values of growth reduction due to soil compaction.

Species	Growth Reduction				Author
	Height	Basal Area	Tree Volume	Stand Volume	
	---------- percent ----------				
Douglas-fir Seedlings	5-50	Summary of literature (percent increases linearly with increase in soil density)			Froehlich 1982
Seedlings	17		48		Froehlich 1982
Seedlings	42				Youngberg 1959
Seedlings	8-21				Froehlich 1978
Seedlings	11-35				BLM (Froehlich 1978)
11-year-old	57			14.5 (est.)	Smith and Wass 1980
17-year-old	29		69	15 (est.)	Froehlich 1978
30-year-old			73	12	Wert and Thomas 1981
70-year-old		14-30			Froehlich and Berglund 1976
Hemlock 22-year-old		15			Froehlich 1980
Loblolly pine 26-year-old			53		Perry 1974
40-year-old		36-43			Moehring and Rawls 1970
Ponderosa pine 64-year-old		6-12			Froehlich 1979

reported in the literature for individual trees. Values quoted for reduction in stand volume should be interpreted with caution.

This report is the outcome of research sponsored by the USDA Forest Service, Region 5, San Francisco, CA. The approach taken was one of four possible research directions suggested by the Principal Investigator after consultation with active researchers in the field of compaction at Oregon State University, USDI Bureau of Land Management, Portland, and Weyerhaeuser Company, Centralia, WA. The particular approach preferred by the Forest Service was to address the question: "To what extent can variability in plantation growth be attributed to variability in soil surface characteristics". The rationale for this approach recognized that young plantations might represent a "worst-case" situation where, after clearcutting and site preparation, the effects of compaction would most likely be evident.

Previous approaches to studies of soil compaction have been either to grow seedlings in compacted soils; evaluate growth differences on or adjacent to known skid trails; or evaluate the effects of increasing numbers of passes of different types of equipment on particular soils. This study utilized a different approach. Within selected plantations, variation in height growth and bulk density were to be determined independently. The relationship between these two characteristics would then be determined. Of particular interest was the desire to obtain direct estimates of the effects of soil surface characteristics on stand growth and development. Soil compaction and site disturbance is probably at a maximum level immediately after harvesting and site preparation. These effects undoubtedly influence initial stand survival and

growth. As time progresses, plantation growth probably ameliorates initial conditions of soil disturbance. This study characterized annual shoot and diameter growth with current conditions of the soil surface and initial levels of soil compaction could obviously not be determined. However it was anticipated that some insights could be obtained regarding plantation growth and surface soil conditions.

METHODS

1. Study Site Selection

Seven National Forests in northern California were contacted for the nomination of plantations that could be suitable for the study. In addition, several private forest landowners were contacted and candidate stands evaluated. Suitable plantations were defined as having resulted from clearcutting, or complete salvage cutting after wildfire, and were to have the following broad characteristics:

1) species: ponderosa pine
2) age: 5-15 yr
3) uniform stocking
4) uniform soils free from stone
5) slopes less than 30 percent
6) little brush competition
7) relatively good site quality

The following National Forest plantations were either visited in the field or screened from data on file in District Offices.

Forest	District	Number of Plantations
Mendocino	Upper Lake	4
Plumas	Greenville	
	Oroville	4
	Quincy	5
	La Porte	4
Tahoe	Downieville	3
	Foresthill	5
Eldorado	Georgetown	3
	Placeville	2
	Amador	2
	Pacific	3
Stanislaus	Calaveras	3
	Miwok	3
	Summit	1
	Groveland	2
Sierra	Bass Lake	1
	Minerets	4
	Kings River	3
Sequoia	Hume Lake	3
	Tule Lake	3

Discussions with U.S.D.A. Forest Service District personnel, examination of plantation records, and field inspections with Dr. Earl Alexander (Watershed Management) and Glenn Davies (Timber Management) from the U.S.F.S. Regional Office, resulted in the selection of two study areas:

1) Burntline 70 Plantation on the Groveland District of the Stanislaus National Forest. (Crane Compartment No. 5 T2N R18E S36). This plantation was 6 years old in 1980, is at an elevation of 5500 feet, has a north aspect, and a 2-8 percent slope. Soils are mostly of the Holland series. The plantation was established on the Granite Burn of August 1973 which was salvage-logged in December 1973. It was planted

to 1-0 ponderosa pine at 10 x 10 foot spacing in the Spring of 1975 (seed lot number 122-531.55).

2) Plantation 7 on the Foresthill District of the Tahoe National Forest (McBride Compartment No. 215, T15N R11E S33-34). This plantation was 15 years old in 1980, is at an elevation of 4300 feet, has a southwesterly aspect, and a 3-5 percent slope. Soils are of the Aiken series. Site class is Dunning 1A. The plantation was established after the Volcano Burn of 1960 and planted to 1-0 ponderosa pine at 8 x 8 foot spacing in the Spring of 1966 (seed lot number 122-111).

PROCEDURES

Twelve 20 x 20 m contiguous plots were established in the Foresthill plantation and ten at Burntline in the summer of 1981. Plot layout was chosen to maintain as much uniformity as possible in soil characteristics, plantation stocking, and to minimize the presence of shrubs. Most of the field work was completed in the summer of 1981 with some of the Foresthill data gathered in 1982. Laboratory analyses of soils, data reduction and analyses were done in the fall and winter of 1982/83.

Within each plot, the following measures were taken:

A. Vegetation

1) the position of each tree and its crown area was mapped.

2) the crown area of each shrub was mapped.

3) each tree was measured in terms of:

diameter at breast height

total height

length of each annual internode since planting

base of live crown

annual radial increment at breast height

4) competition was evaluated in terms of:

percent of tree crowns overlapping shrubs (5 classes: 0-20, 20-40, 40-60, 60-80, 80-100 percent).

percent of tree crowns overlapping grass (3 classes: 0-20, 20-60, and 60-100 percent).

the number of neighbor trees (1 through 4 as expected from square spacing.

B. Soil Surface

1) bulk density -- using a Campbell Pacific 2-probe Strataguage (Appendix A). Sampled at 3 depths (4, 8, and 12 inches) at each of 4 positions around the drip-line of the crown of each tree. Each location around each tree was also ranked from 1 to 3 in terms of visual evidence of soil compaction.

2) depth of A-horizon -- based on moist value of 3 or less using 10.0 YR Munsell color chart.

3) organic carbon and mineralizable nitrogen (for details of procedures see Appendix B) -- on 6 trees per plot, the two tallest, two smallest, and two intermediate-sized trees: four positions per tree, three depths at each position, with 200 gm samples at each depth bulked to provide one sample for each of the three depths of 0-4, 4-8, and 8-12 inches.

4) on one plot (Foresthill Plot 5, 38 trees; Burntline Plot 2,

25 trees) bulk density measured at 3 depths at each of 8 positions around the drip line of the crown of each tree.

5) the existence of skid trails, landings, and burn piles were noted on the map.

RESULTS

A. FORESTHILL PLANTATION

Twelve 20 x 20 plots were established as shown in Figure 1. The location was selected to cross an observed old landing and skid trail/haul road system which had been planted to trees. These features were still observable on 1966 aerial photography taken after site preparation and planting. Shrub cover was approximately 10 percent and consisted of Ceanothus intergerrimus and C. prostratus, with some Arctostaphylos mariposa, A. patula, and Ribes spp. The number of samples or measures taken included 423 trees, 5,076 soil samples, 10,152 soil density readings, and 1,692 measures of A-horizon depth.

1. Soil Characteristics: The soil and parent material were described by Dr. Earl Alexander as an Aiken Series on andesitic lahar with a depth to hard rock of 2-3 m. The soil surface is a loam with about 1 percent andesitic coarse pebbles, cobbles, stones, and boulders. Fine gravels constituted 2-9 percent of the 0-3cm soil surface. Table 2 describes the soil profile.

2. Within-plantation variation in total tree height: Heights ranged from 11.48 to 40.03 ft with a mean of 27.08 $\pm$ 0.22 ft. Within-plantation variability in individual tree heights was evaluated at age 15 years. Stratification was done subjectively by assigning each of 9

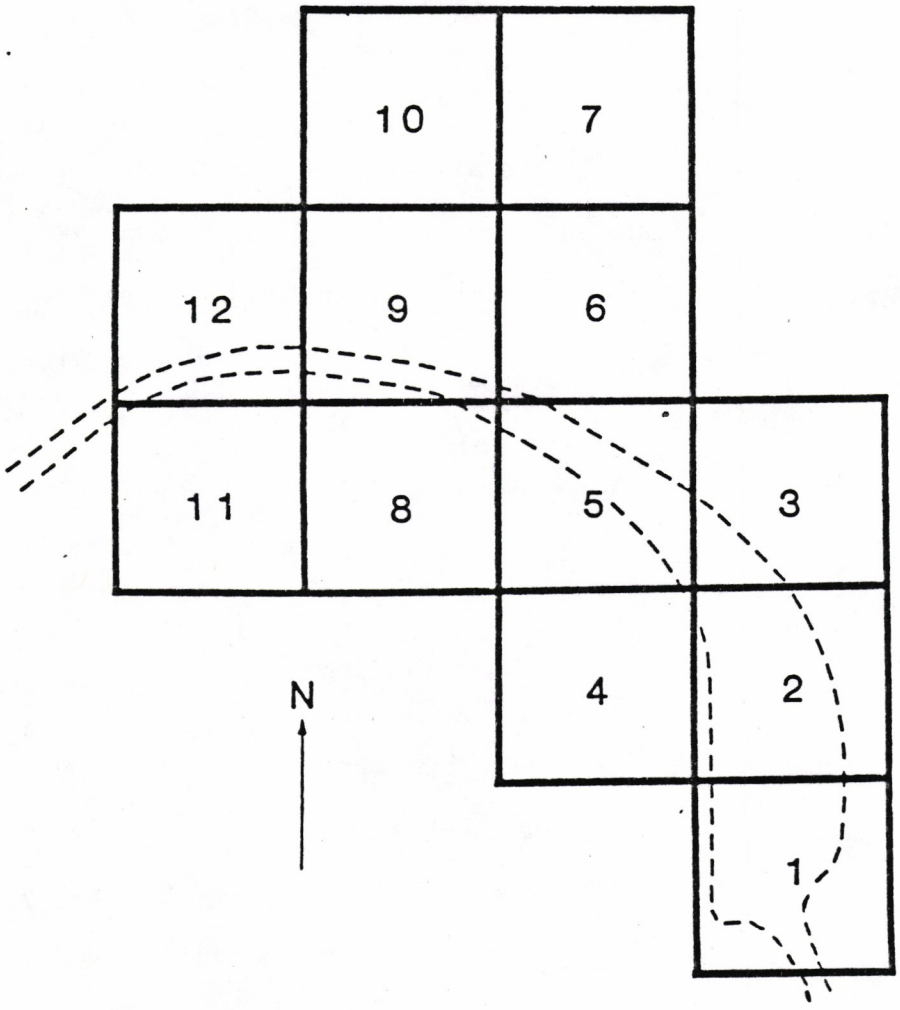

FIGURE 1: Plot layout, Foresthill study area. Each plot is 20 x 20 m. Dashed line shows location of skid trail/haul road and landing.

TABLE 2: Profile description of Aiken loam soil from Foresthill. [from E. Alexander]

Horizon		Depth (cm)	Color dry	Color moist	Texture	pH
	0	3-0	Loose pine needles			
A11	1	0-4	5YR 4/3	5YR 3/3	l	6.0
A12	2	4-18	5YR 4/3	5YR 3/3	l	6.3
B_1	3	18-36	5YR 4/6	2.5YR 3/4	l	6.2
B_{21t}	4	36-75	5YR 5/6	2.5YR 4/5	cl+	5.8
B_{22t}	5	75-120	5YR 5/6	5YR 4/6	cl+	5.7
B_3	6	120-175+	7.5YR 5/6	7.5YR 4/6	gcl-	5.6

levels of total height (4,5,6,....12 m) a different color of increasing intensity and marking each tree on the map appropriately. This procedure was also followed at plantation ages of 5 years (7 levels, $\leq$0.5, 1.0,1.5....$\geq$3.5 m) and at age 3 years (11 levels, $\leq$0.2, 0.3, 0.4 ....$\geq$1.2 m). In each case it seemed reasonable to divide the study area into only two classes (Figures 2,3, and 4). The differences in total height, and the length of the annual shoot produced, at each age is illustrated in Figure 5. At each age, the difference between mean tree heights and between mean annual shoot growth length of the two classes is significant (α - 0.01).

3. Within-plantation variation in diameter: Stem diameters ranged from 2.0 to 11.2 inches with a mean of 7.36 $\pm$ 0.07 in. Using the same procedure, as with height of dividing the range in diameter into 11 levels, no reasonable stratification into diameter classes could be obtained. The distribution of diameters over the 12 plots was highly mixed.

4. Within-plantation variation in bulk density: One-way analysis of variance showed that, for each depth, the variation in mean bulk density among trees was significantly greater (α = 0.01) than the variation among the four measures of bulk density per tree. For each of the three depths, the four measures of bulk density taken around each tree were averaged to provide a single bulk density value which, for all depths, ranged from 0.678 to 1.270 gm/cc with a mean of 0.946 $\pm$ 0.005 gm/cc. The distribution across the study area of soils at different levels of bulk density was examined using a procedure similar to that used for height and diameter; each of the eight levels of bulk density (0.6, 0.7,

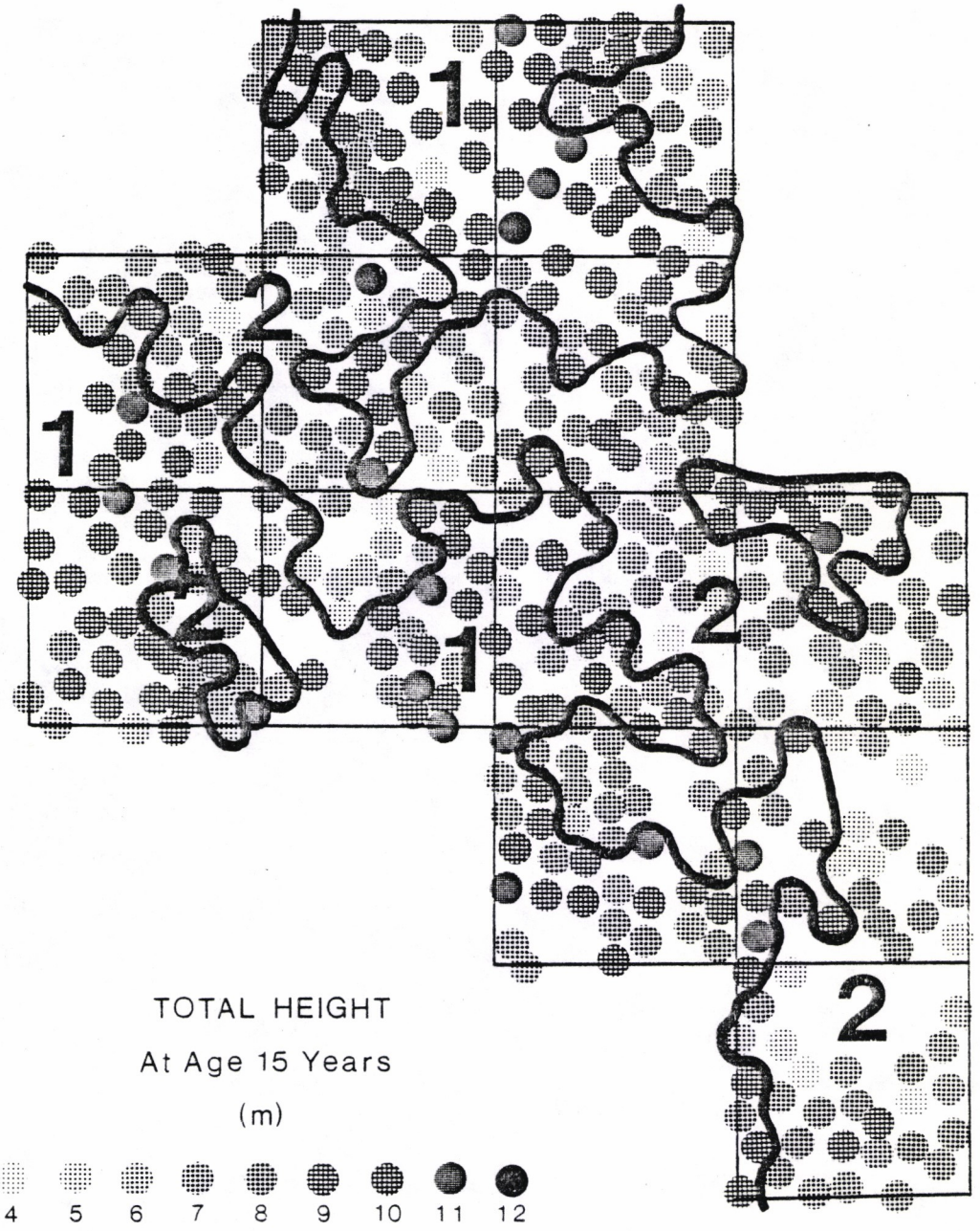

FIGURE 2: Study area at Foresthill. Each tree assigned a color according to its total height at age 15 yr. Area stratified into two height classes: 1 $\geq$ 9m; 2 $\leq$ 8m.

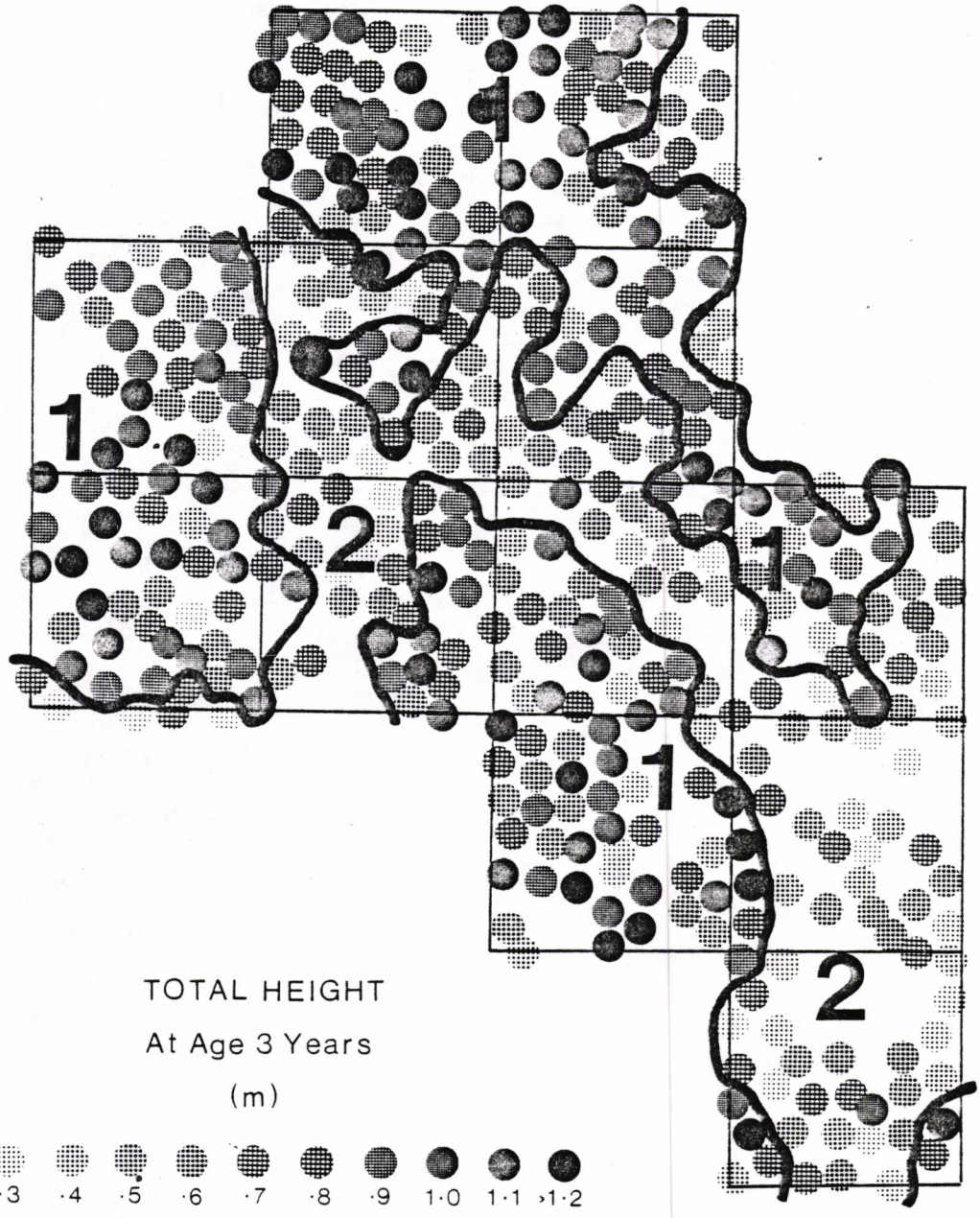

FIGURE 3: Study area at Foresthill. Each tree assigned a color according to its total height at age 3 yr. Area stratified into two height classes: 1 $\geq$ 0.8m; 2 $\leq$ 0.7m.

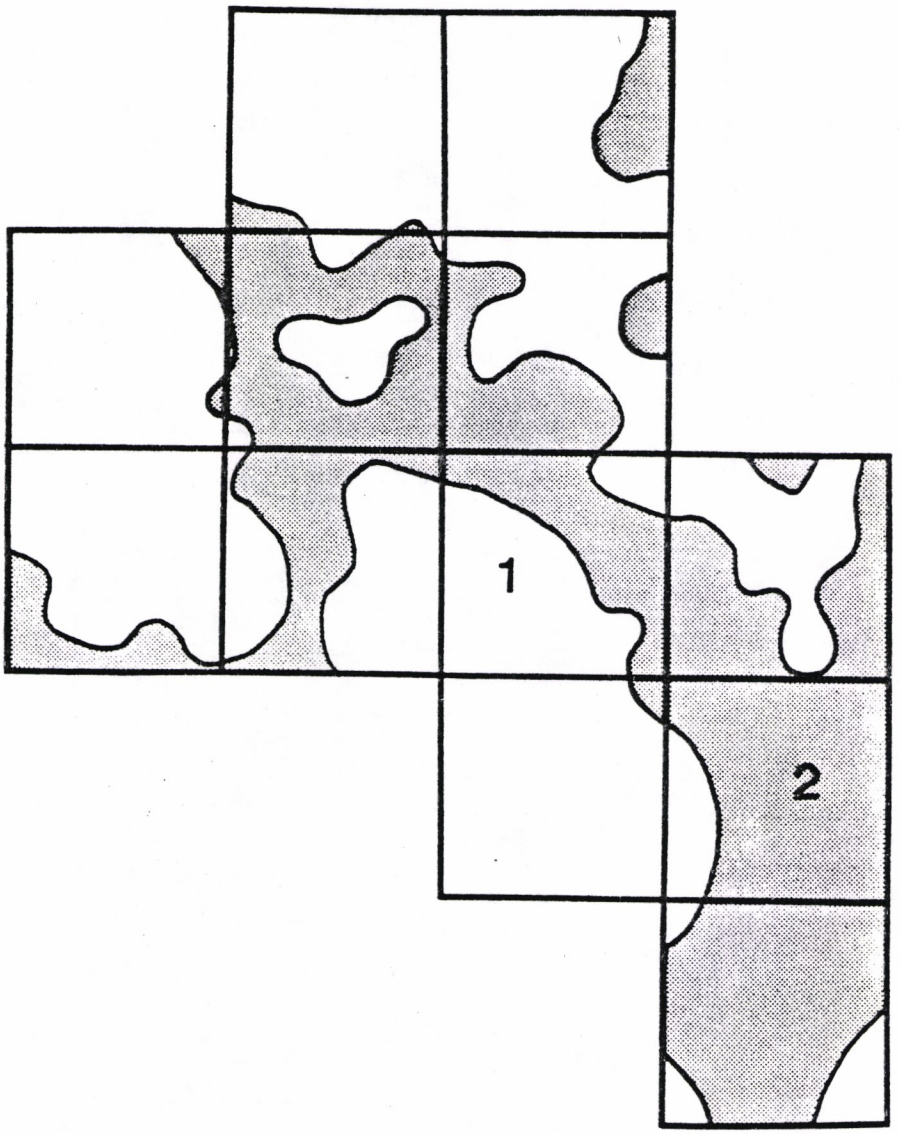

FIGURE 4a): Study area at Foresthill showing stratification into two height classes at 3 years of age.

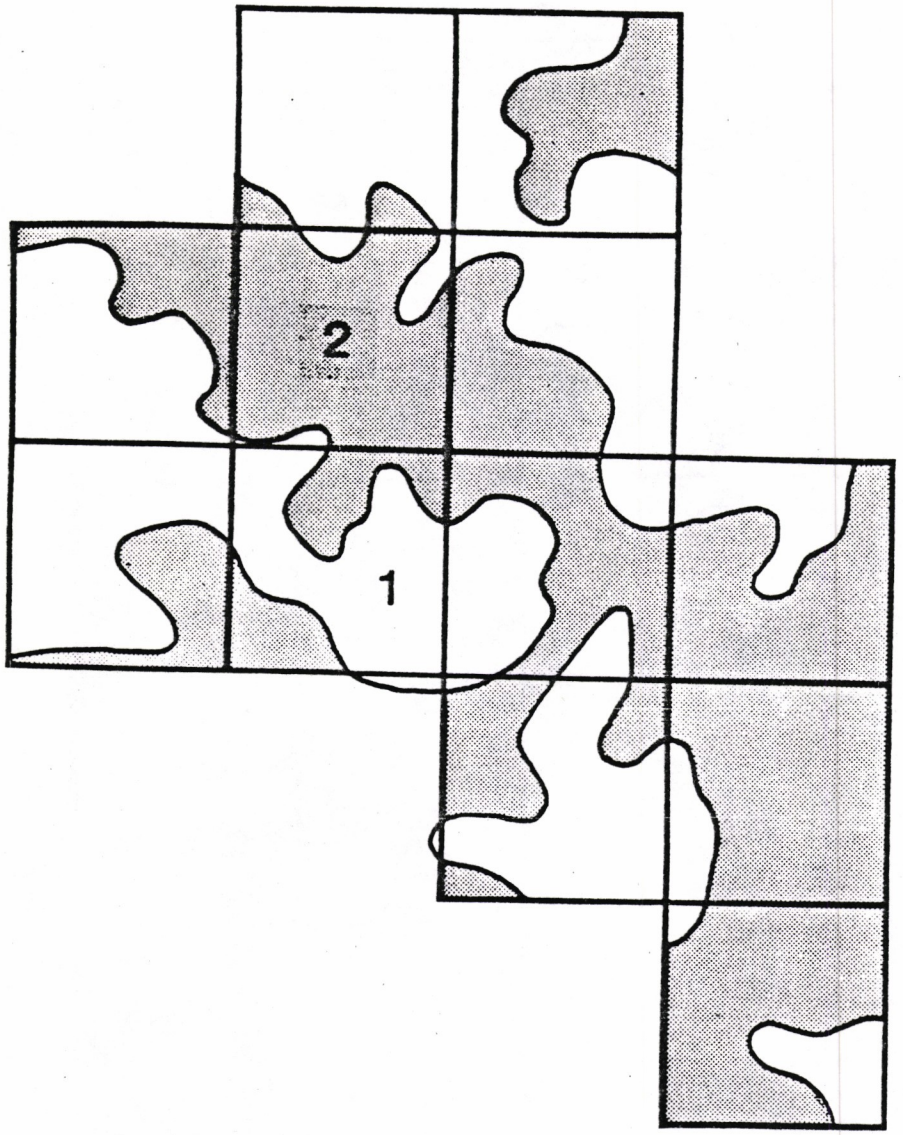

FIGURE 4b): Study area at Foresthill showing stratification into two height classes at 5 years of age.

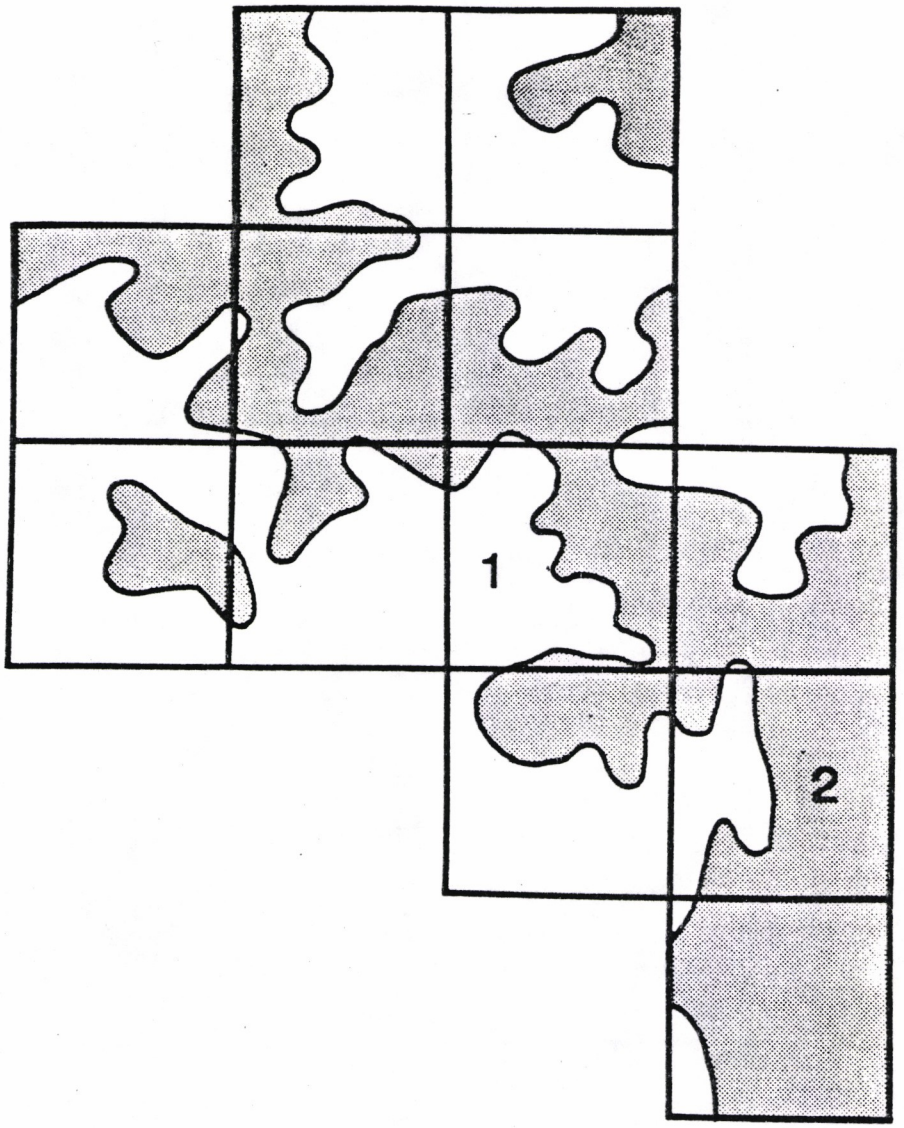

FIGURE 4c): Study area at Foresthill showing stratification into two height classes at 15 years of age.

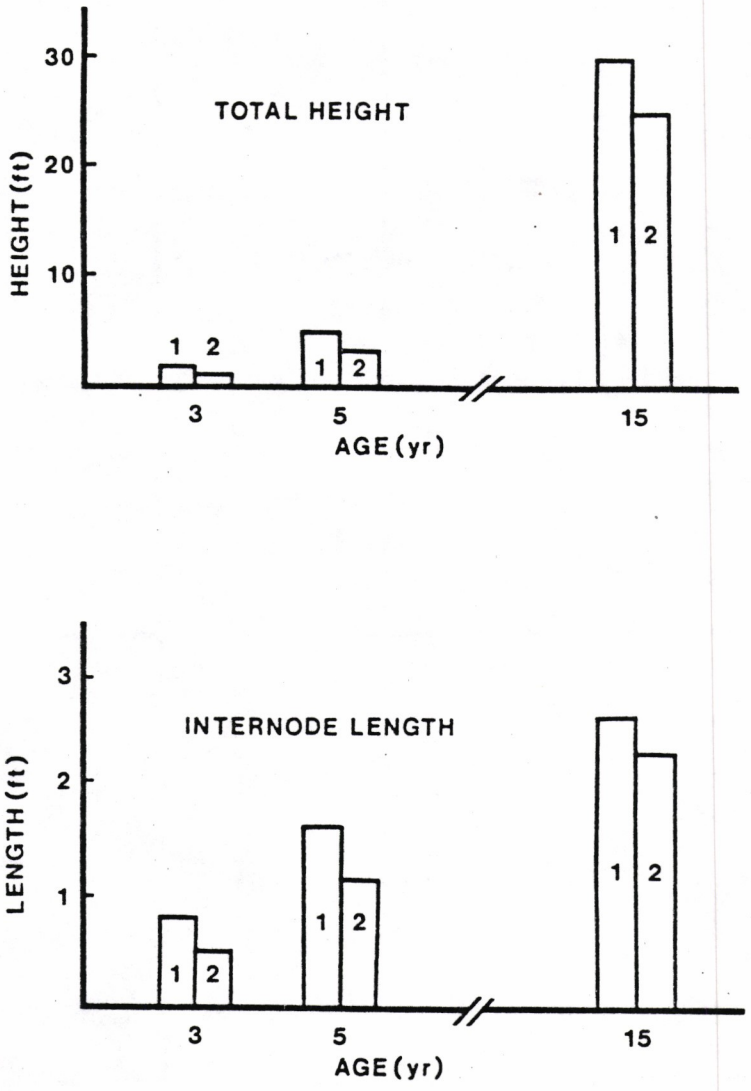

FIGURE 5: Total height and internode length within each height class at Foresthill at ages 3, 5, and 15 years. In each case, differences between each pair of means is significantly different ($\alpha = 0.05$).

0.8, ...1.3 gm/cc) was assigned a color which increased in intensity with increasing bulk density, and each tree on the map was marked appropriately. Four maps were prepared, one for each of the 4-, 8-, and 12-inch depths and one for pooled bulk density where all values for the four positions and three depths per tree were averaged. The variability in bulk density was examined separately for each depth and the area divided into 4 classes. Figure 6 a,b,c,d show the resulting stratification into 4 classes for each depth. Figure 7 illustrates the actual distribution of bulk density levels for the pooled data and the resulting stratification into 4 classes. Of particular interest is the observation that Class 1, with bulk density of 1.1 and greater, has a similar areal extent at the 4-, 8-, and 12-inch depths. Bulk density classes 2, 3 and 4 are not so consistent between depths, but some similarity exists particularly between the 8- and 12-inch depth. A comparison of the distribution of bulk density measures at the 4-inch depth compared with that at other depths suggests that there has been a homogenization of soil characteristics, or amelioration of compaction, at the surface. Table 3 shows the proportion of the study area in each bulk density class at a given depth. A comparison of Figures 6 and 7 shows different boundaries between the four classes. For each depth, the difference in bulk densities between the classes in highly significant. Table 4 shows the mean bulk densities of each class together with the standard errors of each mean.

The original bulk density class 1 was subsequently separated into two sub-classes, 0 and 1, with sub-class 0 being that area of the landing with pooled bulk density measures generally in excess of 1.2 gm/cc (Figure 6). The mean bulk densities of sub-classes 0 and 1 were found

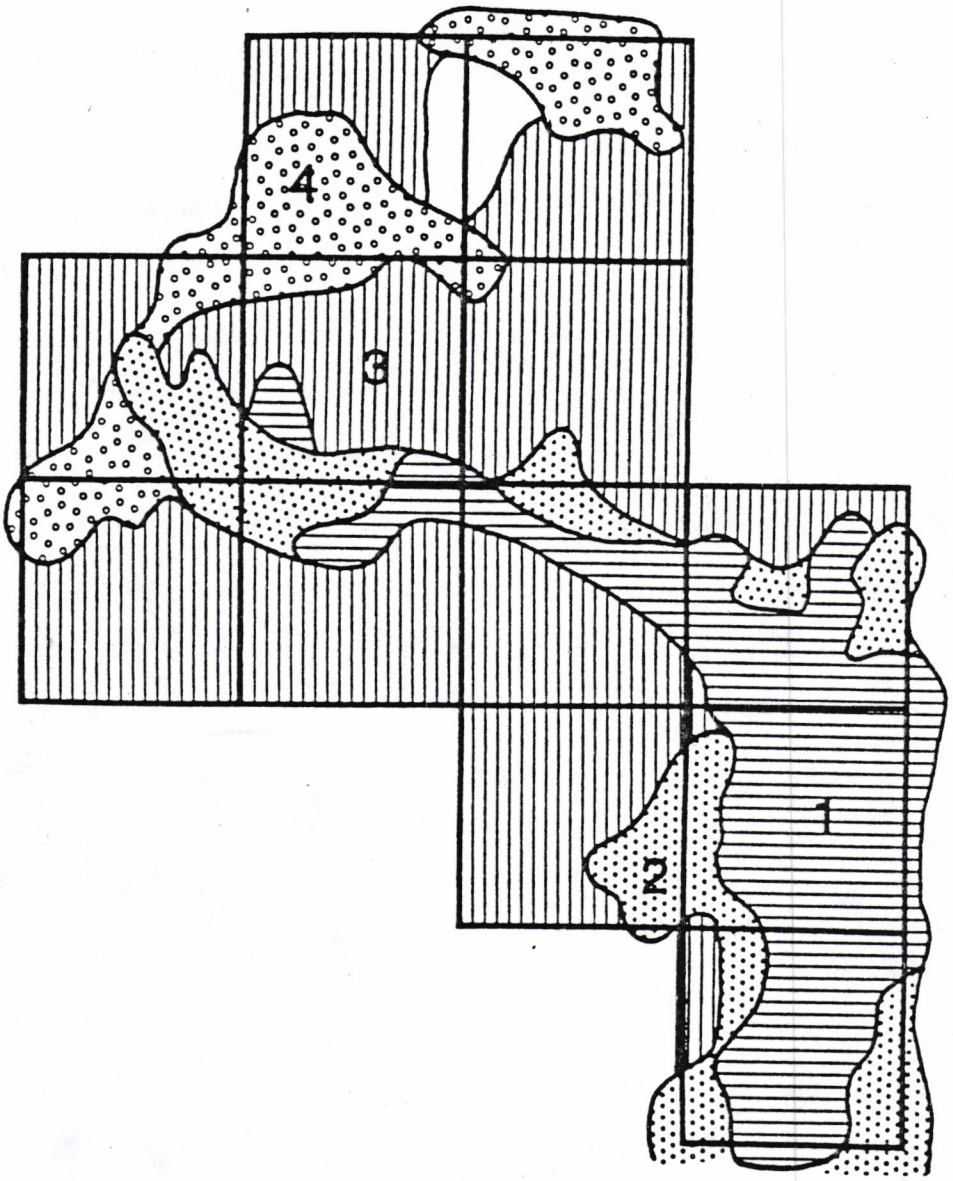

FIGURE 6(a): Study area at Foresthill showing stratification into four levels of bulk density. The blank area represents a major burn pile.

a) 4-in depth: 1=1.13; 2=0.98; 3=0.88; and 4=0.84 gm/cc.

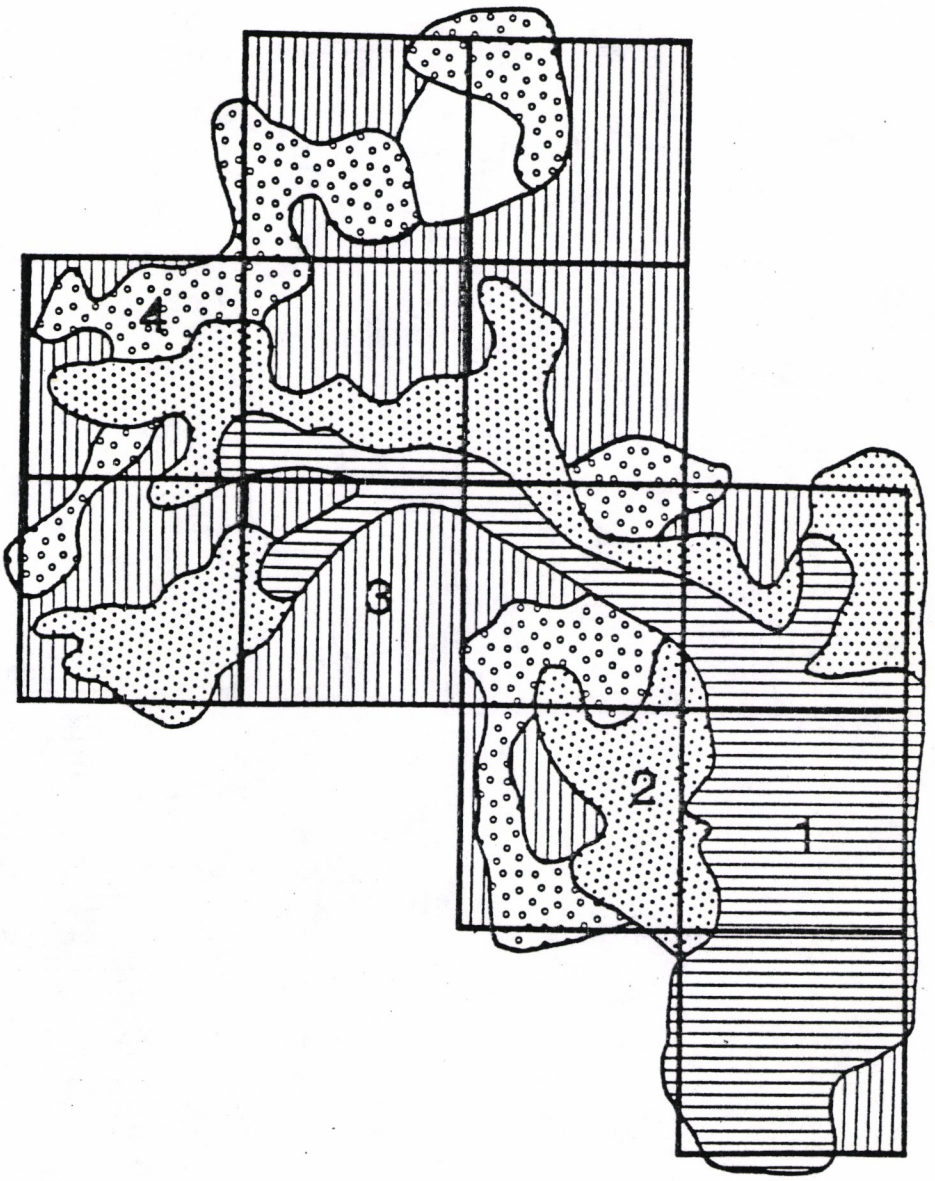

FIGURE 6(b): Study area at Foresthill showing stratification into four levels of bulk density. The blank area represents a major burn pile.

b) 8-in depth: 1=1.14; 2=0.99; 3=0.90; and 4=0.83 gm/cc.

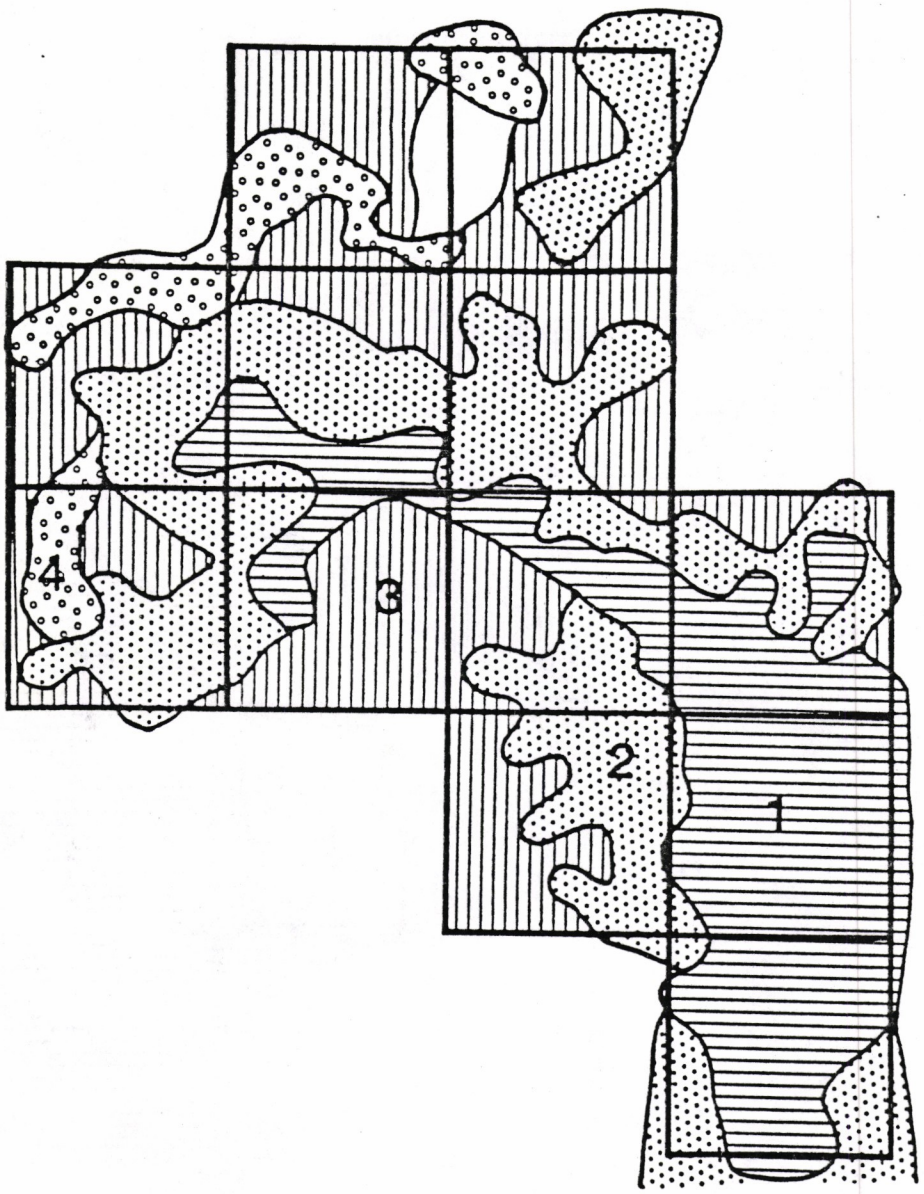

FIGURE 6(c): Study area at Foresthill showing stratification into four levels of bulk density. The blank area represents a major burn pile.

c) 12-in depth: 1=1.12; 2=0.98; 3=0.90; and 4=0.82 gm/cc.

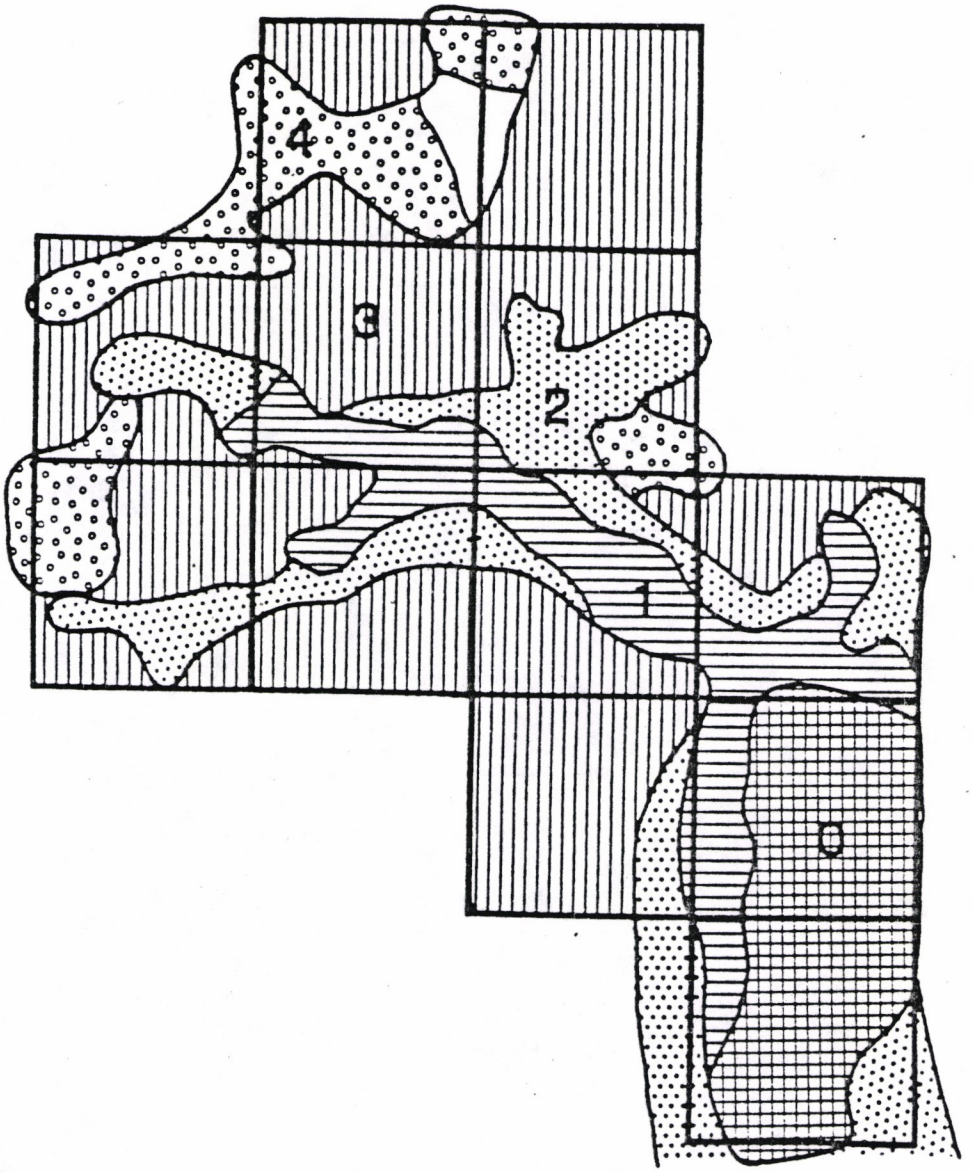

FIGURE 6(d): Study area at Foresthill showing stratification into four levels of bulk density. The blank area represents a major burn pile.

d) pooled depths: 0=1.19; 1=1.08; 2=0.98; 3=0.90; and 4=0.83 gm/cc.

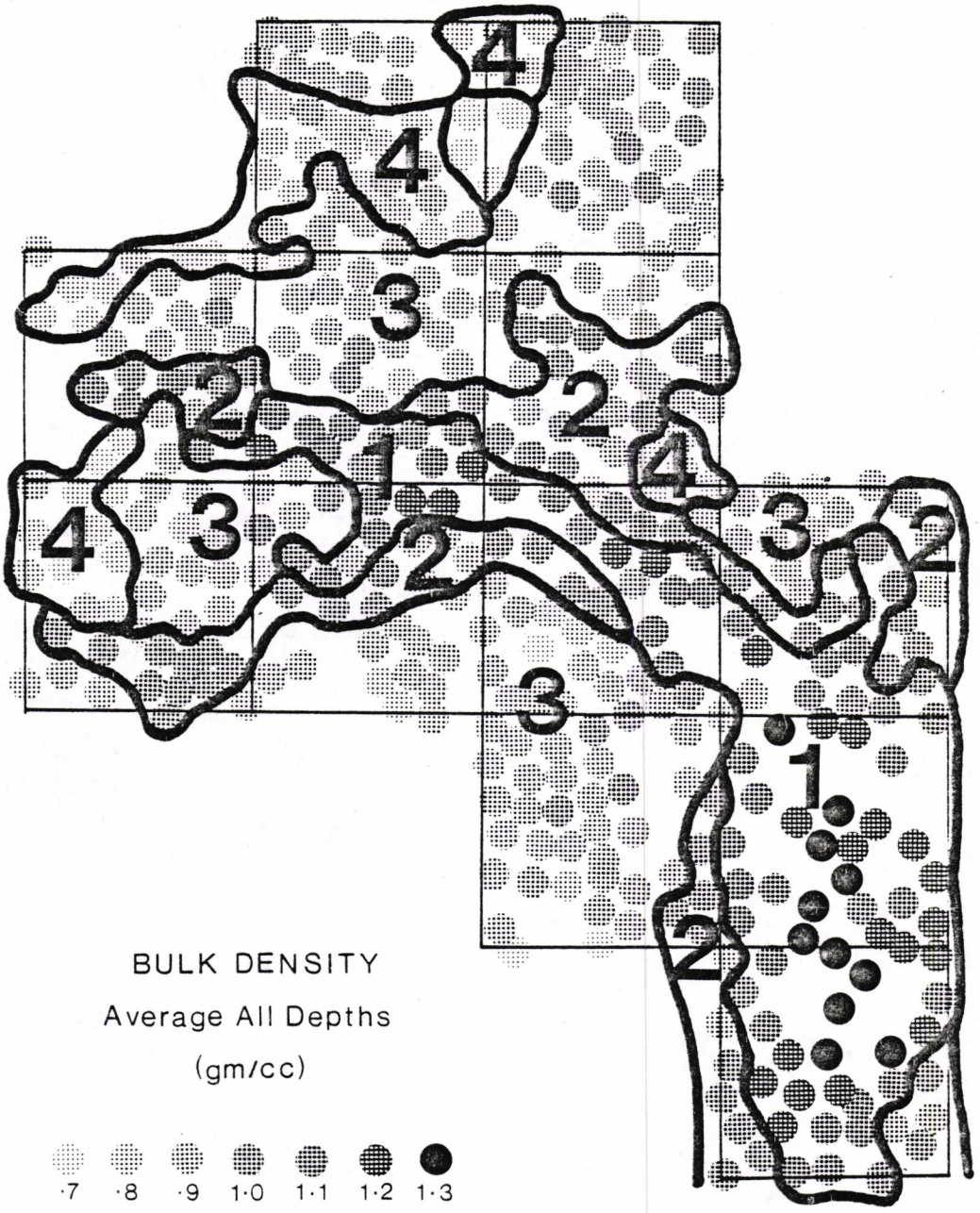

FIGURE 7: Study area at Foresthill. Each tree assigned a color according to its pooled bulk density. Area stratified into 4 classes of bulk density: 1 $\geq$ 1.1; 2=1.0; 3-0.9; 4 $\leq$ 0.8 gm/cc.

TABLE 3: Proportions of study area of Foresthill with soil at levels of bulk density.

Depth (in)	Bulk Density Class				Burn Pile
	1	2	3	4	
	----percent of area----				
4	20	16	52	10	2
8	22	27	40	9	2
12	18	34	36	10	2
Pooled	30	18	40	10	2

TABLE 4: Mean bulk density and standard errors of each bulk density class at each of three depths of Foresthill.

Depth (in)	Bulk Density							
	Class 1		Class 2		Class 3		Class 4	
	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE	$\bar{X}$	SE
4	1.13	0.009	0.98	0.006	0.88	0.003	0.84	0.005
8	1.14	0.009	0.99	0.006	0.90	0.003	0.83	0.006
12	1.12	0.007	0.98	0.004	0.90	0.004	0.82	0.007
$\bar{X}$	1.12	0.008	0.98	0.004	0.90	0.003	0.83	0.004

to be 1.19 and 1.08 gm/cc respectively. The differences between these means is highly significant. Using these values, together with those in Table 4 provided the nominal bulk densities of each of the 5 classes as shown in Table 5.

5. Bulk density differences of the two height classes: The mean tree heights in the two height classes were shown to be highly significantly different (Figure 5). The question to be answered is whether these two height classes differ significantly in soil bulk density. Table 6 shows the mean bulk density at each depth for each of the two height classes at plantation age 15 yr. The differences between the mean bulk densities for each height class at each depth, and for all depths pooled, are highly significant.

6. Height growth differences of the four bulk density classes: The mean bulk densities at each depth, and all depths pooled per tree, were shown to be highly significantly different between all four bulk density classes (Table 4). The next question to be answered is whether the five bulk density classes differ significantly in terms of tree growth.

a) Total Height. The annual development of total plantation height within each bulk density class was calculated. Heights attained at ages 3, 5, and 15 years, together with the standard errors of the means, are shown in Table 7. The general trend of height growth within each bulk density class is shown in Figure 8. The significance of the differences in mean height at each age and within each bulk density class is shown in Table 7 and 8a. It can be seen from these Tables and Figure 9 that the height attained by trees in the composite bulk density class 1 in each year since establishment is highly significantly lower

TABLE 5: Nominal bulk density of each class at Foresthill.

	Bulk Density Class				
	0	1	2	3	4
Bulk Density (gm/cc)	1.2	1.1	1.0	0.9	0.8

TABLE 6: Mean bulk density at each depth for each of the two height classes at Foresthill at age 15 yr.

	Height Class	
	1 (ft)	2 (ft)
Height at 15 yrs (ft)	29.2	24.6
Depth (in)	---- Bulk Density ---- (gm/cc)	
4	0.894 ± 0.006	0.966 ± 0.009
8	0.917 ± 0.006	0.987 ± 0.010
12	0.934 ± 0.006	0.995 ± 0.008
$\bar{X}$	0.915 ± 0.006	0.983 ± 0.008

TABLE 7: Mean total height, and standard errors, of the Foresthill study area at ages 3, 5, and 15yr for each bulk density class. Lines indicate means that are not significantly different at $\alpha = 0.05$. Class 1 is the mean of sub-classes 0 and 1.

Depth (in)	Age 3 Bulk Density Class 1	2	3	4	Age 5 Bulk Density Class 1	2	3	4	Age 15 Bulk Density Class 1	2	3	4
	----- Height (ft)-----				----- Height (ft) -----				----- Height (ft) -----			
4	1.0 0.06	1.4 0.09	1.5 0.04	1.8 0.09	2.8 0.12	3.8 0.19	4.1 0.08	4.5 0.18	24.3 0.53	26.8 0.65	27.6 0.30	28.1 0.54
8	1.0 0.06	1.4 0.06	1.6 0.05	1.7 0.07	2.8 0.13	3.9 0.13	4.2 0.11	4.5 0.13	24.2 0.51	27.0 0.44	27.9 0.36	28.2 0.44
12	1.0 0.07	1.4 0.06	1.6 0.05	1.7 0.09	2.8 0.14	3.8 0.11	4.4 0.10	4.5 0.16	24.0 0.54	26.9 0.36	28.4 0.34	28.0 0.61
$\bar{X}$	1.0 0.07	1.4 0.06	1.6 0.04	1.8 0.08	2.8 0.14	3.9 0.12	4.1 0.09	4.6 0.15	24.1 0.54	27.4 0.40	27.8 0.31	27.7 0.61

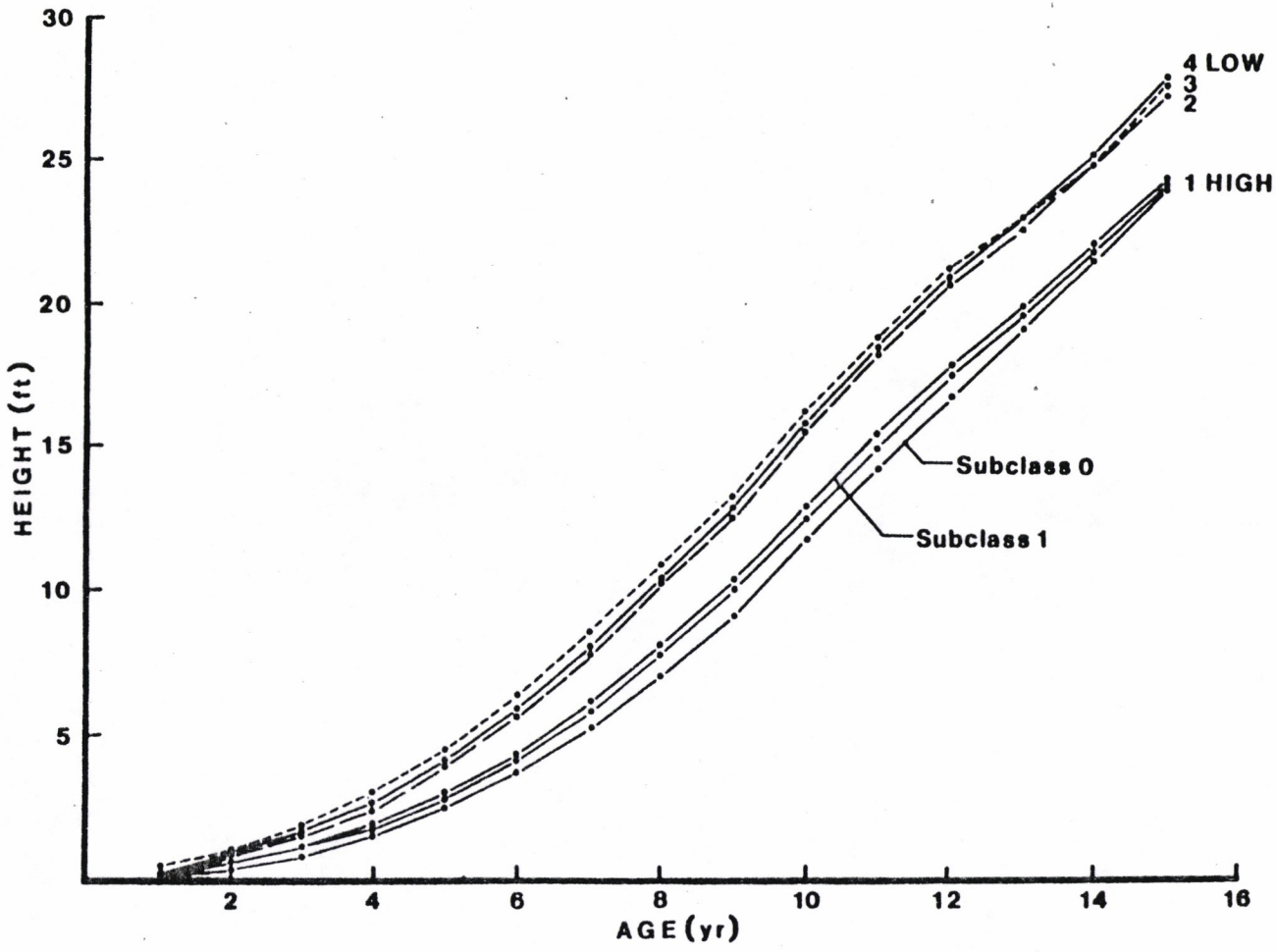

FIGURE 8: Mean total height growth of trees within each bulk density class at Foresthill.

TABLE 8: Significance of differences in tree growth between the four classes of bulk density.

SIGNIFICANCE OF DIFFERENCES IN TREE GROWTH
BETWEEN FOUR CLASSES OF BULK DENSITY

a) TOTAL HEIGHT

Bulk Density Class	Bulk Density	TOTAL HEIGHT 1966	67	68	69	70	71	72	73	74	75	76	77	78	79	80
1 compared with 2	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
1 compared with 3	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
1 compared with 4	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
2 compared with 3	S															
2 compared with 4	S	S	S	S	S	S	S	S								
3 compared with 4	S				S	S										

b) INTERNODE LENGTH

Bulk Density Class	Bulk Density	INTERNODE LENGTH 1966	67	68	69	70	71	72	73	74	75	76	77	78	79	80
1 compared with 2	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
1 compared with 3	S	S	S	S	S	S	S	S	S	S	S	S				
1 compared with 4	S	S	S	S	S	S	S	S	S	S	S					
2 compared with 3	S															
2 compared with 4	S	S	S									S		S		
3 compared with 4	S				S							S		S		

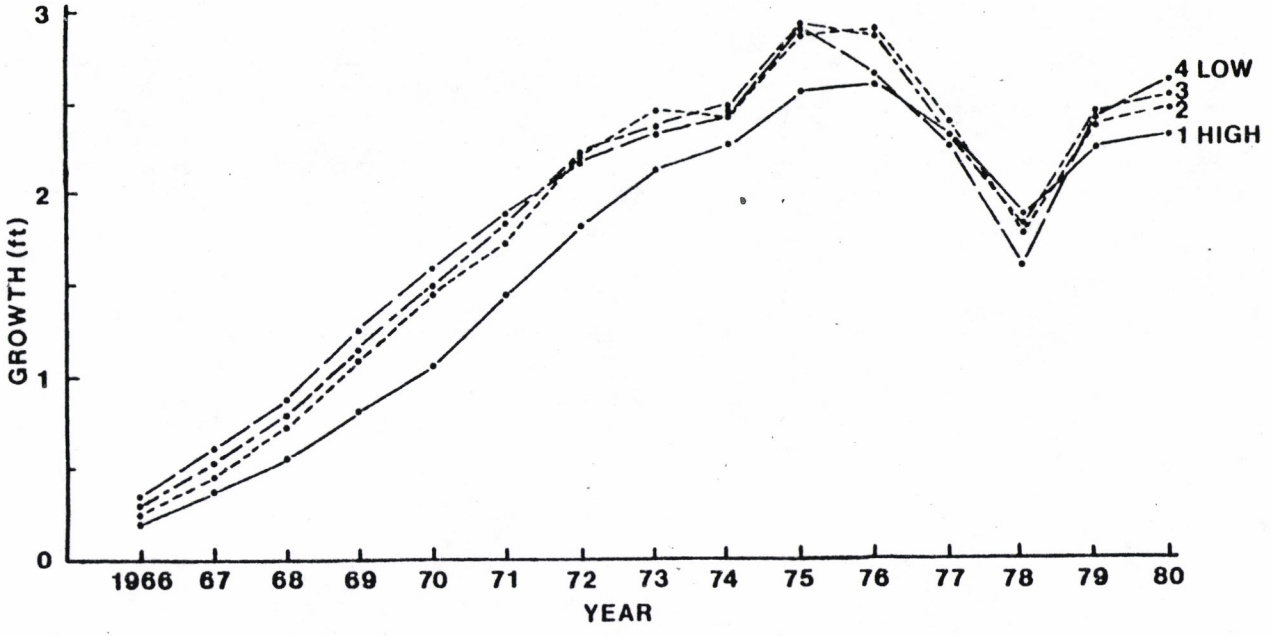

FIGURE 9: Mean annual shoot growth for each year from 1966 to 1980 for each bulk density class at Foresthill.

TABLE 9: Annual shoot-growth and standard errors, at Foresthill at ages 3, 5, and 15yr for trees growing in each bulk density class. Lines indicate means that are not significantly different at $\alpha = 0.05$. Class 1 is the mean of sub-classes 0 and 1.

INTERNODE LENGTH

Depth (in)	Age 3 Bulk Density Class 1	2	3	4	Age 5 Bulk Density Class 1	2	3	4	Age 15 Bulk Density Class 1	2	3	4
	--- Shoot Growth (ft) ---				--- Shoot Growth (ft) ---				--- Shoot Growth (ft) ---			
4	0.5 0.04	0.6 0.07	0.8 0.02	0.8 0.05	1.0 0.05	1.4 0.06	1.4 0.03	1.5 0.06	2.4 0.08	2.2 0.08	2.5 0.07	2.6 0.08
8	0.5 0.04	0.6 0.04	0.8 0.03	0.8 0.04	1.0 0.04	1.4 0.04	1.5 0.04	1.5 0.05	2.3 0.07	2.4 0.07	2.5 0.08	2.6 0.13
12	0.5 0.03	0.6 0.03	0.8 0.03	0.8 0.05	1.0 0.04	1.4 0.04	1.5 0.04	1.5 0.06	2.3 0.06	2.4 0.06	2.6 0.09	2.6 0.07
$\bar{X}$	0.5 0.03	0.7 0.04	0.8 0.02	0.8 0.04	1.0 0.05	1.4 0.04	1.4 0.03	1.6 0.06	2.3 0.65	2.4 0.08	2.5 0.08	2.6 0.10

than that in the other bulk density classes. Some significant differences in height growth occur between bulk density classes 2, 3, and 4 but in general the differences are small.

b) Annual Shoot Growth. Table 9 presents examples of the annual shoot growth produced at ages 3, 5, and 15 years together with the standard errors of the means. The complete sequence of annual internode length produced in each bulk density class is illustrated in Figure 9. The significance of the differences in mean shoot growth at each age and within each bulk density class is shown in Tables 8b and 9. Similar to the analysis of total height, it can be seen that the length of the annual shoot growth produced in the class of highest bulk density is consistently significantly shorter than that produced in bulk density classes 2, 3, and 4, from the time of establishment until 1975 when the plantation reached 10 years of age. Table 8 shows that in some years, there is a significant difference in annual shoot growth between bulk density classes 2, 3, and 4, but in general these differences appear to be of relatively little practical importance.

An examination of Figures 8 and 9 suggests that the rate of height growth of trees in bulk density class 1 is less than that for height growth in the other bulk density classes from the time of establishment in 1966 through the 1970 growing season. From 1971 through 1975, the difference between annual shoot growth in class 1 and the other classes appears to be gradually diminishing with time. These observations suggest that soil compaction has probably resulted in a pronounced reduction in the rate of height growth in the soils which currently have bulk density of from 1.1 - 1.3gm/cc (class 1) for the first five years after establishment. From age 5 through 10 years, this difference in rate of

height growth gradually diminished. However, at age 10 (1975) the shoot growth in bulk density class 1 was still highly significantly less than that in the other three classes.

Figure 9 shows that the annual shoot growth in each year from 1966 through 1971 diminishes with increasing bulk density. From 1972 through 1975 annual shoot growth in classes 2, 3 and 4 was essentially the same but significantly greater than in bulk density class 1. The remarkable reduction in annual shoot growth in the 1977 and 1978 growing seasons may be partially explained by examining records of monthly precipitation for the period 1971 through 1980 (Figure 10). These data, taken from weather records at Placerville, CA, shows the marked reduction in precipitation for both the winter of 1975/76 and 1976/77. Precipitation in both of these winters was approximately 40 percent of that in the other years of that decade. It appears from Figure 9 that the reduced precipitation in the winter of 1975/76 resulted in normal shoot growth in bulk density class 1, 2 and 3. However in class 4, with the lowest bulk density of less than or equal to 0.8gm/cc, a substantial reduction in shoot growth occurred. The general lack of a reduction in growth in 1976 may be because the reduced rainfall in the previous winter was generally adequate to enable full elongation of the stem units that existed in the terminal shoot. The dry summer of 1976, followed by a second winter of below normal precipitation in 1976/77, resulted in a marked reduction in shoot growth in 1977 in all bulk density classes. This reduction is probably associated with both fewer primordia being laid down in the bud in 1975 and with reduced elongation of the individual stem units in the drought year of 1976. The winter of 1977/78 produced normal rainfall, but probably due to fewer primordia being laid down in the bud during

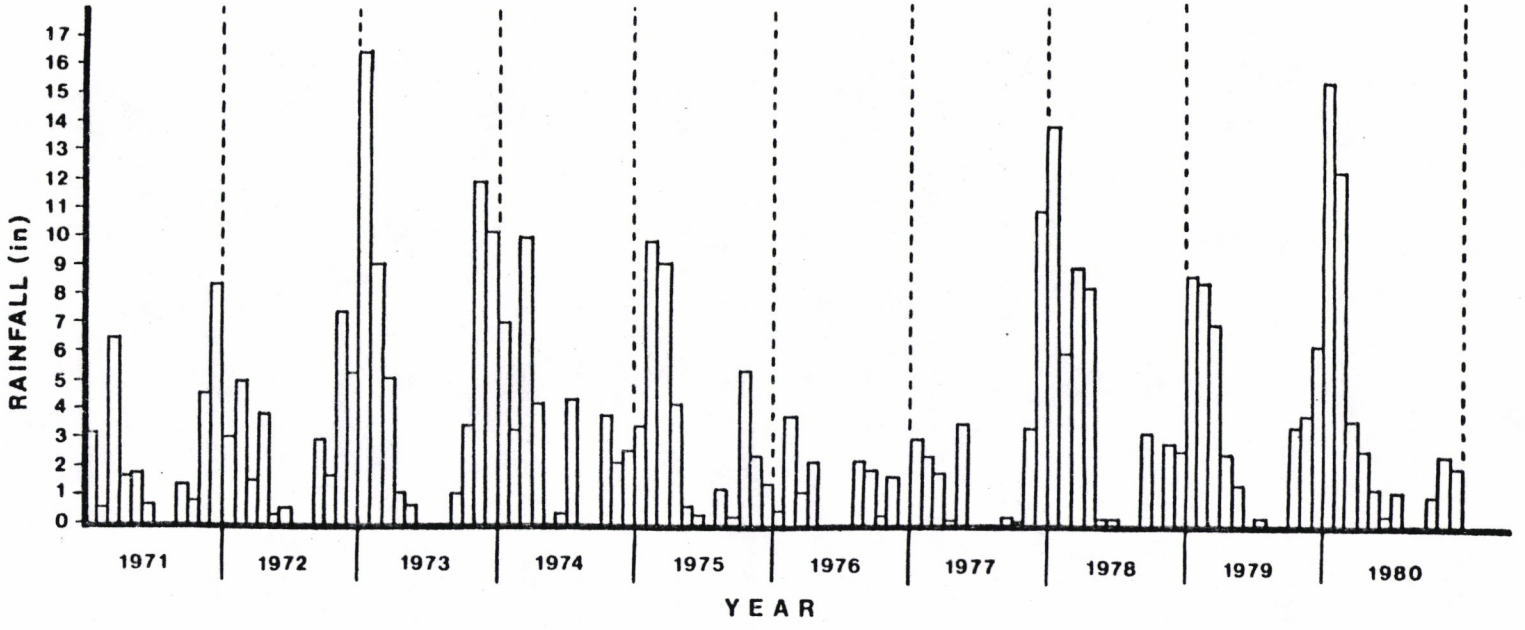

FIGURE 10: Monthly precipitation at Placerville, California, for the period 1971 through 1980.

1977, shoot growth in 1978 was even more reduced than in the previous year. Shoot growth in 1979 recovered substantially, but did not reach pre-drought levels probably because of the cumulative effects of reduced soil water storage and reduced growth reserves in the trees after two successive years of below-normal precipitation. Even shoot growth in 1980, after three winters of normal precipitation, did not reach pre-drought levels indicating that two years of drought affect subsequent height growth for at least four years.

It is also apparent from Figure 9 that the reduction in annual shoot growth associated with drought is greatest in soils with the lowest bulk density. It is possible, therefore, that in this Aiken loam, increasing bulk density up to 1.1 -1.3gm/cc enhances soil water retention and capillary flow which ameliorates the effect of the drought. In contrast, the soils with lowest bulk density had the largest macro pore space and probably lost water more rapidly through transpiration than the soils with higher bulk density.

7. Correlation Analysis: Correlation analysis was used to determine the importance of a single independent variable in estimating total height and annual shoot growth throughout the life of the plantation. Figures 11a, b, and c show the change in simple correlation with age of the plantation. Each figure shows the difference in correlation coefficient for each soil characteristic at each depth. In general, Figure 11a shows that at each age, the density measures that is most highly correlated with total height and annual shoot growth is the average bulk density with bulk density at the 4-inch depth being least correlated. It can also be seen that the correlation varies with age, reaching a

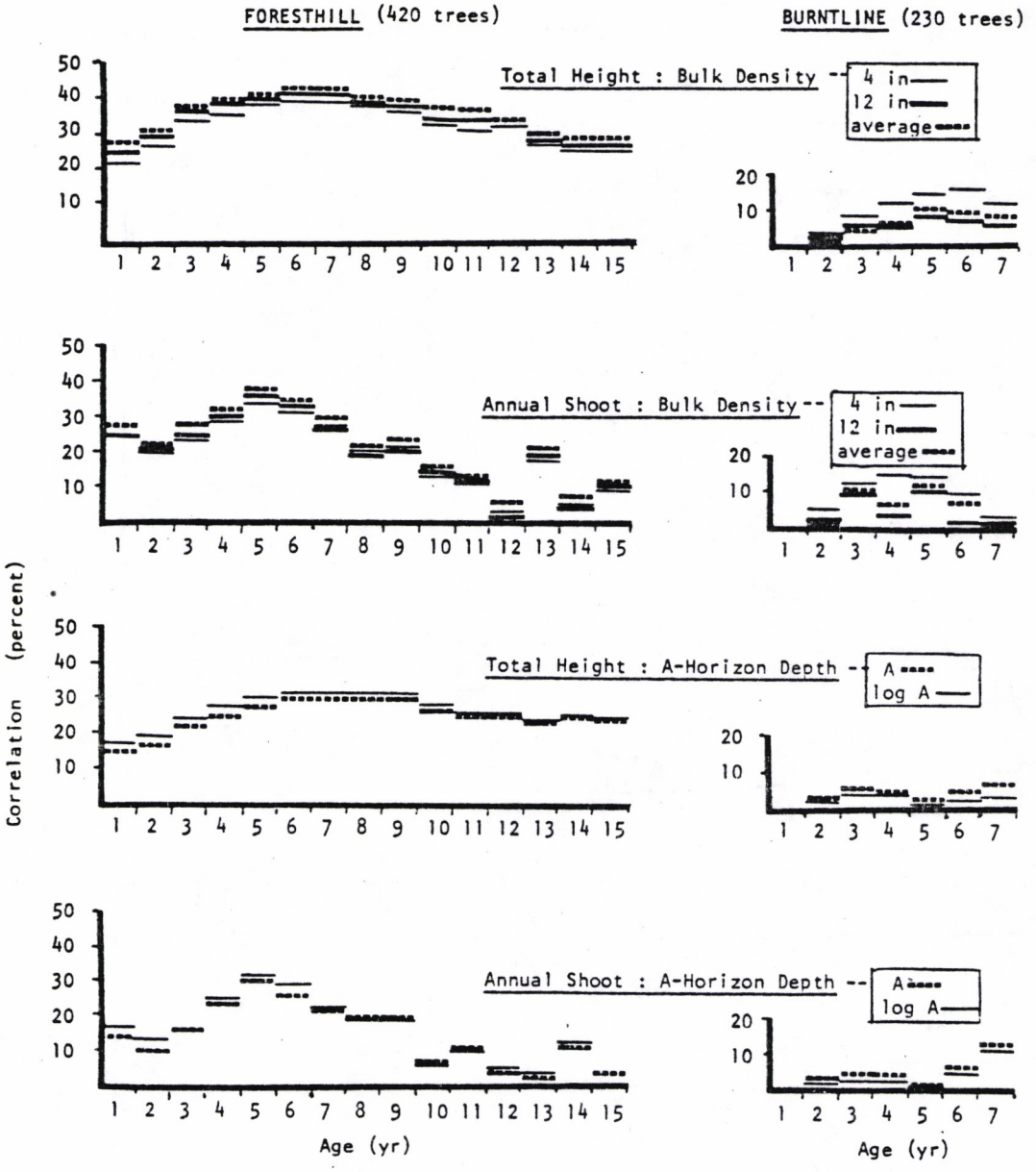

FIGURE 11a): Simple correlations between independent and dependent variables at Foresthill and Burntline in successive years after establishment: a) bulk density and A-horizon depth.

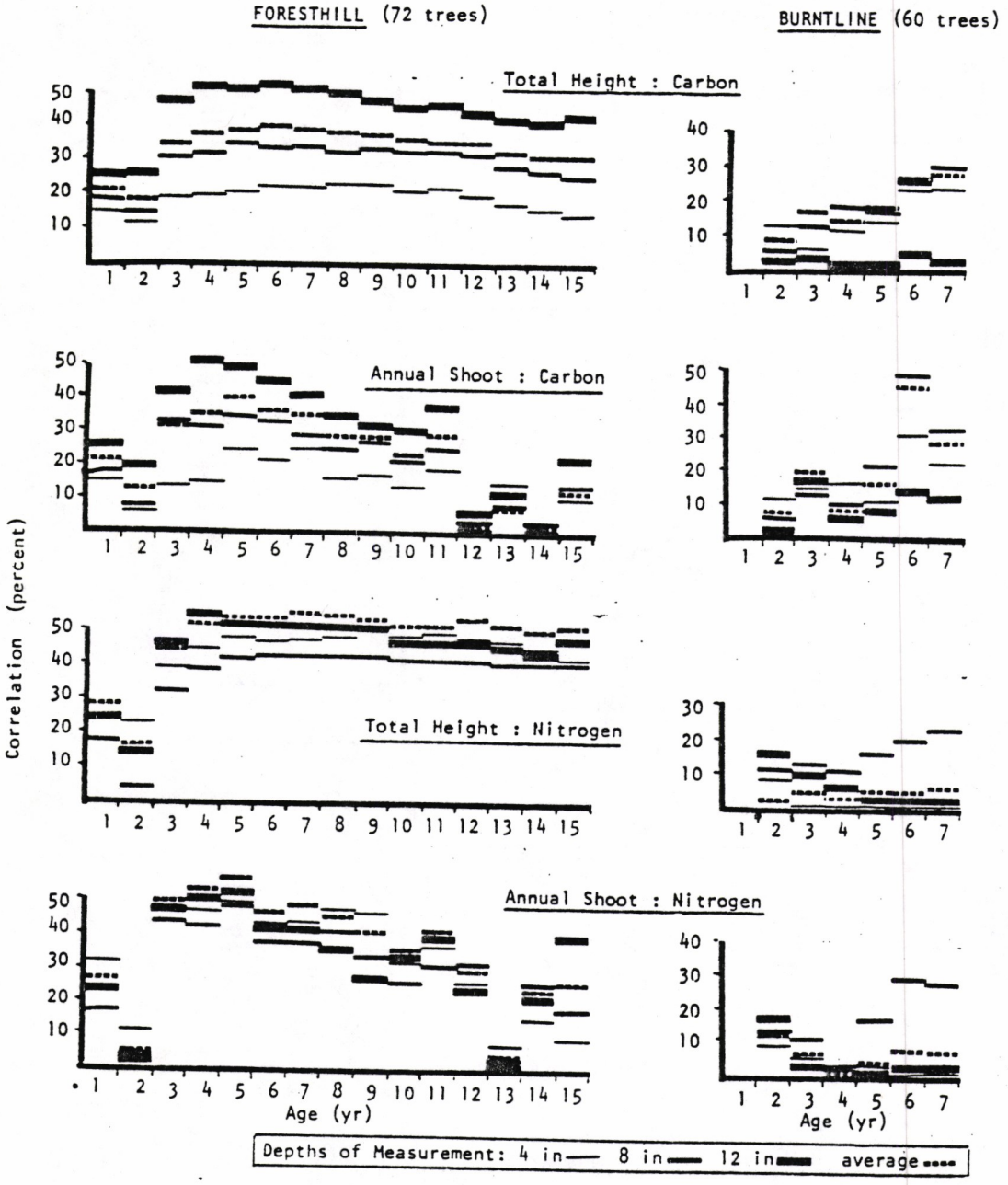
FORESTHILL (72 trees)
BURNTLINE (60 trees)
Total Height : Carbon
Annual Shoot : Carbon
Total Height : Nitrogen
Annual Shoot : Nitrogen
Correlation (percent)
Age (yr)
Depths of Measurement: 4 in 8 in 12 in average

FIGURE 11b): Simple correlations between independent and dependent variables at Foresthill and Burntline in successive years after establishment: b) organic carbon and mineralizable nitrogen.

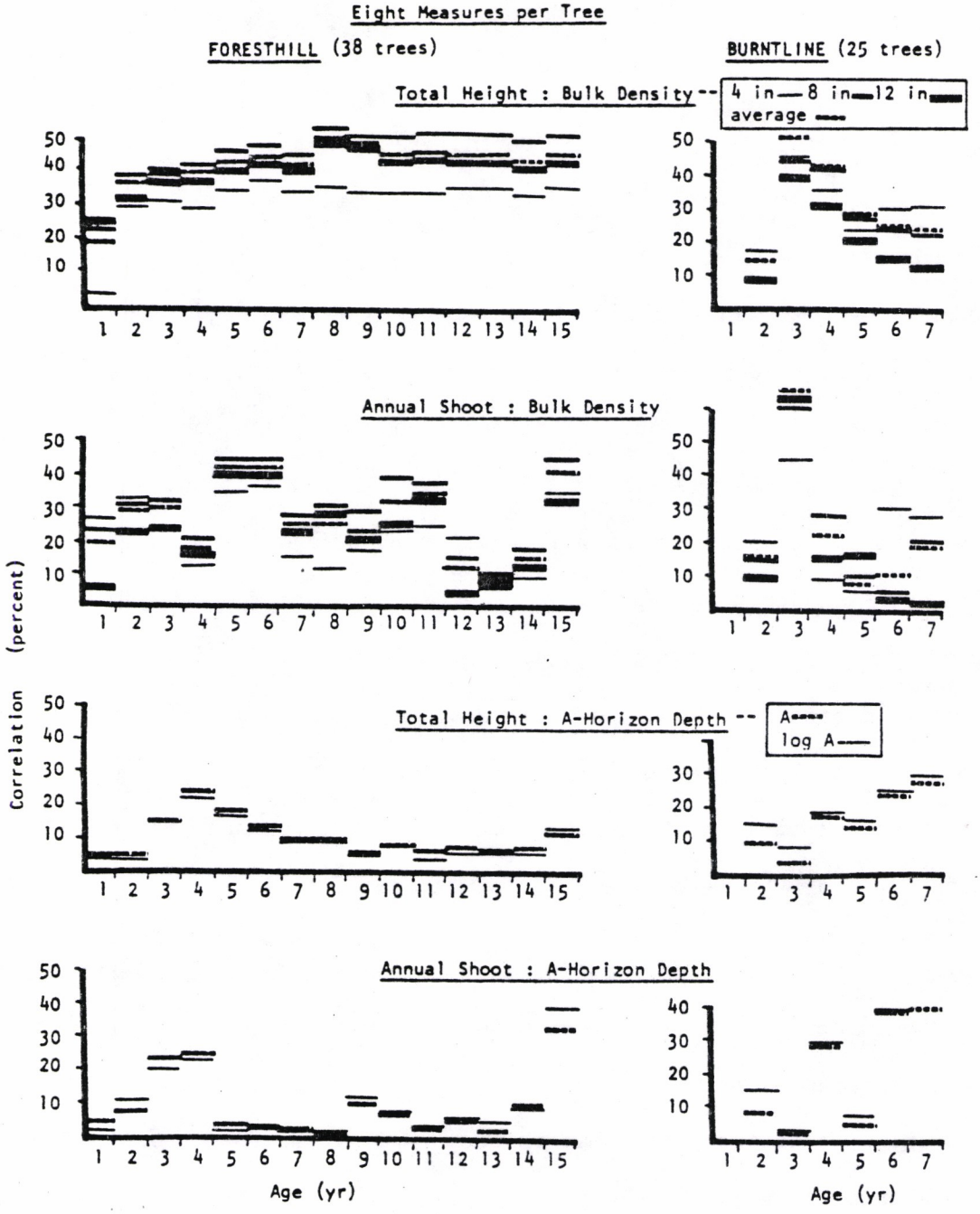

FIGURE 11c): Simple correlations between independent and dependent variables at Foresthill and Burntline in successive years after establishment: c) Bulk density and A-horizon depth measured at eight positions per tree.

maximum of 40 percent at age 6 to 7 years for total height and about 5 years for annual shoot growth. A-horizon depth reaches a maximum correlation with total height of 30 percent between the ages 6 to 9 years. Figure 11b shows that the extent to which organic carbon is correlated with total height depends markedly on depth. Between the ages of 6 and 7 years, carbon at the 12-in depth has a correlation of 52 percent whereas carbon at the 4-in depth has a correlation of 23 percent. Similarly with respect to annual shoot growth at age 5 years, organic carbon has a correlation of 50 percent at the 12-in depth, but only 24 percent at the 4-in depth. In the case of mineralizable nitrogen, correlation with total height growth reaches a maximum at age 7 years of 55, 51, 47 and 43 percent for average nitrogen from all depths, and nitrogen at the 12-in, 4- and 8-in depth respectively. The correlation of mineralizable nitrogen with annual shoot growth appears to gradually diminish after age 5 years. Increasing the number of positions of bulk density measures per tree from 4 to 8 raises the correlation coefficient from a maximum of 40 percent to 50 percent, and increases the importance of measures at the 8-in depth over those at other depths (Fig. 11c).

The correlation analyses indicate that measures of bulk density, organic carbon and mineralizable nitrogen will probably be more important variables than A-horizon depth in accounting for variability in tree growth. It also appears that these <u>current</u> measures of soil surface characteristics are more closely correlated with tree growth at ages 5-8 years than with growth at an earlier or later age.

8. <u>Multiple Regression Analysis</u>: Multiple regression analysis techniques were used to address the question as to what extent variation

in tree growth is attributable to variation in soil surface characteristics.

a) Using all 420 trees in the study area.

Independent variables used were:

average bulk density per tree	$\overline{D}$
observed bulk density (visual)	K
shrub competition	Shrub
surrounding tree density	STree
average A-horizon depth per tree	$\overline{A}$

Table 10 presents for each dependent variable the most important three variables and corresponding coefficient of determination (r^2). These data show that only 10 to 20 percent of the variability in tree growth can be attributed to the variables used. Interestingly, of these variables, mean bulk density is the most important, typically being responsible for 70 to 80 percent of the variability that was accounted for. Particularly unimportant variables were the surrounding tree density and visual estimates of compaction. The low proportion of variability in tree growth attributable to bulk density is consistent with the results presented earlier in this report which indicated generally no significant difference in mean height growth between trees in bulk density classes 2, 3 and 4. Table 10 shows somewhat higher r^2 values for tree growth at age 7 than at age 15 yr. This is despite the fact that, using this procedure, one is relating past growth with current conditions of the soil and competition. Using a multiple regression analysis utilizing a backward elimination procedure resulted in almost identical regression equations and coefficients to those shown in Table 10.

TABLE 10: The three most important independent variables accounting for variation in height, internode length, diameter, and radial increment, together with the coefficients of determination (r^2). Foresthill plantation, all trees.

Dependent Variable	Independent Variable	r^2
Height at 15yr	$-\bar{D}$ -Shrub $\bar{A}$	0.13
Height at 7yr	$-\bar{D}$ $\bar{A}$ -Shrub	0.23
Internode 15	$-\bar{D}$ -Shrub K	0.02
Internode 7	$-\bar{D}$ $\bar{A}$ -Shrub	0.11
DBH	$\bar{A}$ -Shrub $-\bar{D}$	0.10
Radial Incr. 15	$\bar{A}$ $-\bar{D}$ -Shrub	0.07
Radial Incr. 7	$-\bar{D}$ $\bar{A}$ -Shrub	0.18

b) Using six trees per plot.

Anticipating that the relationship between tree growth and bulk density would be low, and that growth would also be influenced by micro differences in soil nutrition, additional measures of organic carbon and mineralizable nitrogen were obtained on six trees on each plot. The trees selected for these additional measures were the two tallest, the two smallest and the two intermediate-sized trees per plot. The regression technique used in the analysis of these 72 trees was a stepwise backward elimination procedure.

The independent variables used in this analysis were:

average bulk density per tree	$\overline{D}$
bulk density at 4-in depth	D_4
bulk density at 8-in depth	D_8
bulk density at 12-in depth	D_{12}
visual estimate of compaction	K
mean A-horizon depth	$\overline{A}$
shrub competition	Shrub
surround tree density	STrees
nitrogen at 4-in depth	N_4
nitrogen at 8-in depth	N_8
nitrogen at 12-in depth	N_{12}
average nitrogen per tree	$\overline{N}$
carbon at 4-in depth	C_4
carbon at 8-in depth	C_8
carbon at 12-in depth	C_{12}
average carbon per tree	$\overline{C}$

Table 11 ranks for each dependent variable the most important independent variables in a 9- factor and a 5- factor regression equation together with their corresponding regression coefficients. These data indicate that about 40 percent of the variability in height and diameter growth may be attributed to soil surface characteristics and shrub competition.

Despite possible problems in interpretation due to autocorrelation, it appears that the most important factor is organic carbon at the 12- or 8-in depth, followed by mineralizable nitrogen at the 4-in depth, and average bulk density or density at 12- or 8-in depth.

Additional analyses were made using logarithmic transformations and adding the variable of average percent coarse fragments. Neither the transformations nor the additional variable improved the coefficients of determination.

c) Eight positions of bulk density per tree.

Knowing that soil bulk density varies remarkably within a given area, one plot consisting of 38 trees was sampled using double the sampling intensity, i.e. 8 positions per tree with the usual measures of bulk density being taken at 4-, 8-, and 12-in depths at each position. The plot chosen for this analysis was Plot 5 because it contains areas of all bulk density classes. Multiple regression techniques were used to determine the extent to which variation in tree growth could be explained by the more intensive sampling of bulk density. Also examined was the question as to which measure of bulk density was most effective in accounting for variability in tree growth: bulk density at 4-, 8-,

TABLE 11: Results of a backward elimination regression showing the ranking of dependent variables at an early and later stage of the analysis with corresponding coefficients of determination (r^2).

Dependent Variable	Independent Variables									r^2
Height at 15yr	N_4	N_{12}	$-\bar{D}$	D_8	-Shrub	$-C_4$	$\bar{A}$	D_{12}	$-C_4$	0.45
	N_{12}	N_4	$-C_4$	$-\bar{D}$	D_8					0.39
Height at 5yr	C_{12}	N_4	$\bar{A}$	$-\bar{D}$	D_{12}	-Shrub	$-C_8$	$-C_4$	K	0.51
	C_{12}	N_4	$-C_8$	$\bar{A}$	-Shrub	$-\bar{D}$	D_{12}			0.48
Height at 3yr	C_{12}	$\bar{A}$	$-\bar{D}$	D_{12}	N_4	$-C_8$	-Shrub	$-C_4$	K	0.43
	C_{12}	$\bar{A}$	$-C_8$	$-\bar{D}$	D_{12}	N_4				0.39
DBH at 15yr	C_{12}	$-C_8$	N_8	$\bar{A}$	N_4	D_8	-Shrub	$-\bar{D}$	K	0.44
	C_{12}	$-C_8$	N_4	$\bar{A}$	-Shrub					0.38
Radial Incr. 15	C_{12}	$-C_8$	$\bar{A}$	N_4	N_8	D_8	-Shrub	$-\bar{D}$	K	0.43
	C_{12}	N_4	$-C_8$	$\bar{A}$	-Shrub					0.39
Radial Incr. 10	C_{12}	$-C_8$	$+N_8$	$+\bar{A}$	$+D_8$	$-A11_D$	$+N_4$	+K	$+D_{12}$	0.48
	C_{12}	$+N_8$	$-C_8$	$+D_8$	$-A11_D$					0.43
Radial Incr. 7	C_{12}	$+N_4$	$+N_8$	$+D_8$	$-C_8$	$-A11_D$	$+\bar{A}$	-Stree	$-C_4$	0.47
	C_{12}	$+N_8$	$-C_8$							0.38

12-in or average bulk density. To avoid auto-correction effects, this was done by two separate analyses. Table 12 shows the results of regression analysis using the following independent variables:

bulk density at 4-in depth	D_4
bulk density at 8-in depth	D_8
bulk density at 12-in depth	D_{12}
visual estimation of compaction	K
average A-horizon depth	$\overline{A}$
shrub competition	Shrub
surrounding tree density	STree

Table 12 shows that the two alternative groups of bulk density measures both account for about 20 to 30 percent of the variability in tree growth. There is not a strong consistency in the ranking of independent variables but, in general, bulk density measures at the 8-in and 12-in depth appear to be the most important. Doubling the sampling intensity by measuring bulk density at eight positions per tree rather than four raised the coefficients of determination to 25 to 40 percent. Consistently, the most important variable was bulk density at the 8-in depth. The results of this analysis indicate however that there is little incentive to measure bulk density at more than four positions per tree. In all three analyses the regressions are weak and there are additional concerns in that the sign of some of the variables seems to be inconsistent with what might rationally be expected.

Table 13 shows a similar analysis to that just described except that all measures of bulk density were averaged to provide one measure per tree. Comparisons can be made between the two groups of four posi-

TABLE 12: Results of multiple regression analysis from Foresthill showing the relative importance of four and eight measures of bulk density per tree in accounting for variability in tree growth. Bulk density measures kept separate by depth.

Dependent Variable	Independent Variables			r^2
4 positions per tree: Group A				
Height at 15yr	$-D_8$	+K	$-D_{12}$	0.31
Height at 5yr	$-D_{12}$	+K	$-D_8$	0.38
Height at 3yr	$-D_{12}$	+K	+STree	0.33
DBH at 15yr	$+D_4$	$-D_8$	$-D_{12}$	0.29
4 positions per tree: Group B				
Height at 15yr	$-D_8$	-STree	$+D_{12}$	0.21
Height at 5yr	$-D_8$	-Shrub	$+\bar{A}$	0.33
Height at 3yr	$+\bar{A}$	$-D_8$	$-D_4$	0.16
DBH at 15yr	$-D_8$	$+D_4$	-Shrub	0.20
8 positions per tree				
Height at 15yr	$-D_8$	$+D_4$	$+D_{12}$	0.35
Height at 5yr	$-D_8$	$+D_4$	+K	0.42
Height at 3yr	$-D_8$	+K	+STree	0.24
DBH at 15yr	$-D_8$	$+D_4$	-Shrub	0.37

TABLE 13: Results of multiple regression analysis from Foresthill showing the relative importance of four and eight measures of bulk density per tree in accounting for variability in tree growth. Bulk density measures averaged over all depths.

Dependent Variable	Independent Variables			r^2
4 positions per tree: Group A				
Height at 15yr	$-\overline{D}$	-STree	-Shrub	0.27
Height at 5yr	$-\overline{D}$	-Shrub	+K	0.34
Height at 3yr	$-\overline{D}$	+K	+STree	0.27
DBH at 15yr	$-\overline{D}$	-Shrub	-STree	0.18
4 positions per tree: Group B				
Height at 15yr	$-\overline{D}$	$+\overline{A}$	-STree	0.17
Height at 5yr	$-\overline{D}$	$+\overline{A}$	-Shrub	0.30
Height at 3yr	$-\overline{D}$	$+\overline{A}$	+K	0.15
DBH at 15yr	$-\overline{D}$	-Shrub	-STree	0.16
8 positions per tree				
Height at 15yr	$-\overline{D}$	-STree	-Shrub	0.23
Height at 5yr	$-\overline{D}$	+K	$+\overline{A}$	0.35
Height at 3yr	$-\overline{D}$	$+\overline{A}$	+K	0.22
DBH at 15yr	$-\overline{D}$	-Shrub	-STree	0.19

tions per tree and the use of eight positions per tree. Table 13 shows that mean bulk density per tree is consistently the most important variable. The second most important variable is either A-horizon depth or competition in the form of shrubs or the number of surround trees. Again, 20 to 30 percent of the variability in tree growth can be explained, and no advantage is demonstrated for doubling the intensity of sampling for bulk density.

B. BURNTLINE PLANTATION

Ten 20 x 20m plots were established as shown in Figure 12. No old skid trails could be seen but the plots were located across an area where possible compaction could be observed. Shrub cover was approximately 10 percent (*Ceanothus cordulatus* and *Arctostaphylos patula*), forbs 5 percent (*Phacelia heterophylla*, *Calyptridium umbellatum*, and *Gayophytum nutallii*), and grasses 20 percent (*Dactylis glomerata*, *Bromus tectorum*, and *Stipa californica*). The number of samples or measures taken included 232 trees, 2,772 soil samples, 5,544 soil density readings, and 924 measures of A-horizon depth.

1. *Soil characteristics*: The soils and parent material were described by Dr. E. Alexander (U.S. Forest Service, San Francisco). Soils are Holland and Shaver taxajuncts with sandy loam surface textures. Parent material is granitic till with a depth to hard rock greater than 2m. The Holland soil has less than 1 percent coarse pebbles, and granitic fragments. The Shaver taxajunct has 15-35 percent pebbles and coarser rock fragments. Surface soils (0-30 cm) contained 1-6 percent (by volume) fine gravels. Table 14 describes the profile.

2. *Within plantation variation in height*: Heights ranged from 2.30 to 11.48 ft with a mean of 7.50 $\pm$ 0.09 ft at age 7 yr (1981). Trees were classified into 11 classes of total height and their distribution in the study area was evaluated using similar procedures to those used at Foresthill. Distribution of total height was highly mixed and no possibility of dividing the area into 2 or more height classes was evident. Total height was also evaluated at age 3 yr (1977) and found to range between 0.6 and 2.3 ft. Again it was shown that the area could not be

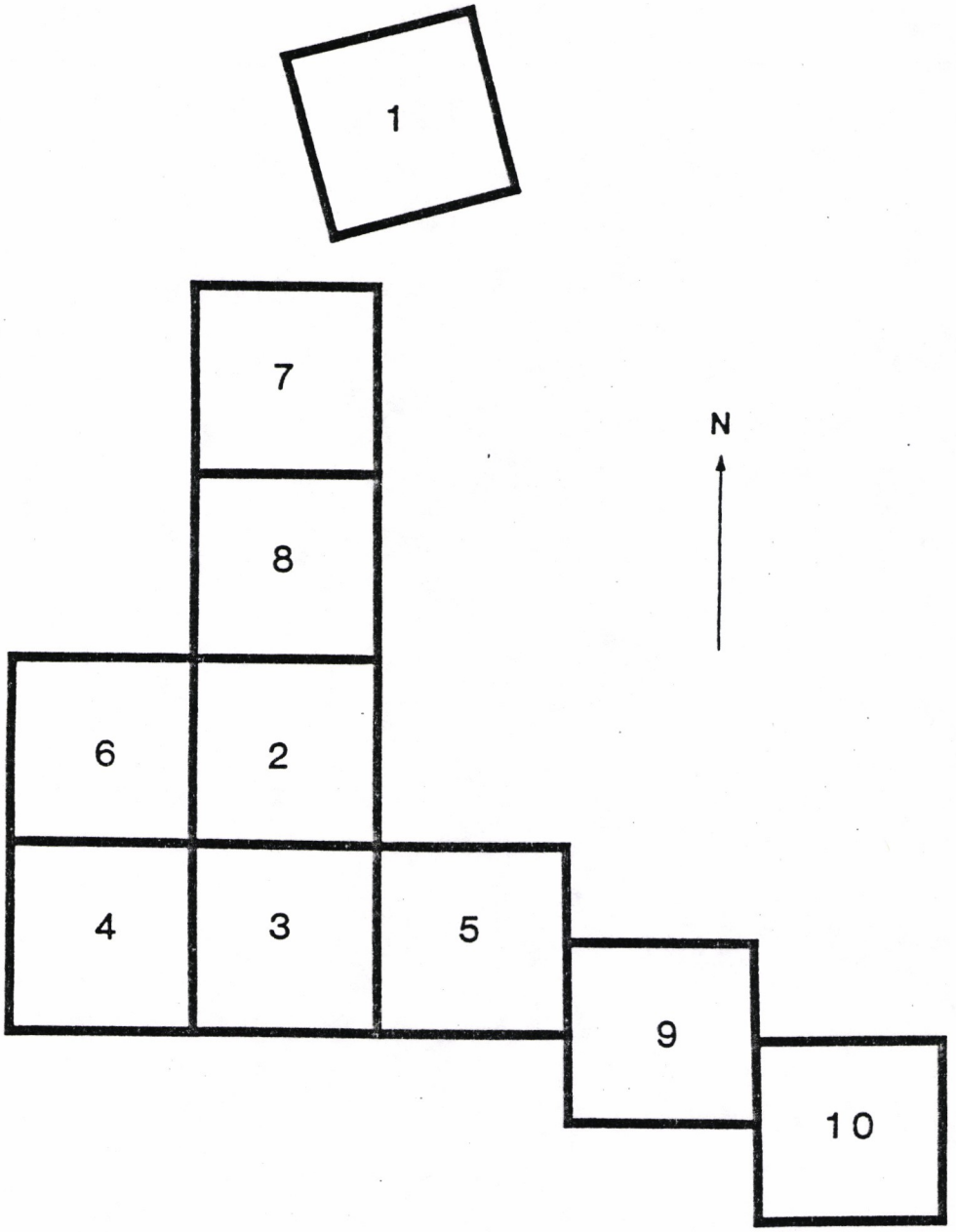

FIGURE 12: Plot layout, Burntline study area. Each plot is 20 x 20 m.

TABLE 14: Profile description of Holland sandy loam from Burntline [E. Alexander].

Horizon		Depth (cm)	Color (dry)	Color (moist)	Texture	pH	Gravel 2-5mm (wt %)	Gravel 5-20mm (wt %)
A11	1	0-5	7.5YR 4/3	5YR 3/2	sl	6.4	4.3	1.3
A12	2	5-18	7.5YR 4/3	5YR 3/3	sl	6.6	4.6	0.9
B_1	3	18-36	5YR 4/4	5YR 3/4	sl+	6.4	2.9	0.8
B_2	4	36-56	5YR 5/6	5YR 4/4	scl+	6.2	3.8	0.2
B_3	5	56-80	5-7.5YR 5/5	5YR 4/4	scl+	5.6	1.8	0.5
C_1	6	80-120	7.5-1.0YR 6/5	7.5YR 5/5	scl	6.0	2.6	0.7
C_2	7	120-180	10YR 6/6	10YR 5/6	scl-	5.8	1.2	0.3
C_3	8	180-240+	10YR 6/5	10YR 5/5	sl	5.4	1.7	0.4

divided into classes of similar tree height. Table 15 shows the mean total height of trees in the study area from age 2 to age 7 (1981) and the length of the annual shoot produced in each year.

3. Within plantation variation in diameter: Diameter at breast height ranged from 0 to 3.40 in with a mean of 1.88 ± 0.04 in. Similar to Foresthill, the distribution of diameters over the 10 plots was highly mixed and the area could not be classified into units of similar-sized stem diameters.

4. Within plantation variation in bulk density: One-way analysis of variance demonstrated that, for each depth, the variation in mean bulk density among trees was significantly greater ($\alpha = 0.01$) than variation among the four measures of bulk density per tree. Bulk densities (averaged from all depths) ranged from 0.781 to 1.378 gm/cc with a mean of 1.099 ± 0.006 gm/cc. This range was divided into 6 classes and an attempt was made to stratify the area into two or more classes of similar soil bulk density. Bulk densities at each of the three depths were highly variable and meaningful stratification was not possible. Part of the difficulty in stratification may have been the more linear arrangement of the plots compared with the distribution at Foresthill.

5. Simple correlation coefficients: Simple correlations were calculated to determine the association between height growth and the major independent variables. This was done to identify which factors might be more important and whether the degree of association varied with increase in plantation age. Results of this analysis are shown in Figure 11a, b, c. It can be seen in this figure that, compared with similar data for Foresthill, no clear trends are evident. Both bulk

TABLE 15: Mean total height and length of annual shoot growth of trees at Burntline at each age from 2 to 7 years.

Age (yr)	Mean Height (ft)	Coeff. of Variation	Internode Length (ft)	Coeff. of Variation
2	0.65 ± 0.02	50.5	0.65 ± 0.02	50.5
3	1.44 ± 0.03	31.4	0.78 ± 0.02	36.0
4	2.70 ± 0.04	26.0	1.27 ± 0.02	29.4
5	4.06 ± 0.06	22.9	1.35 ± 0.02	26.7
6	5.56 ± 0.08	20.7	1.50 ± 0.02	24.8
7	7.50 ± 0.10	19.0	1.95 ± 0.03	21.2

density and A-horizon depth are poorly correlated with total height and annual shoot growth (Figure 11a). Carbon and nitrogen are more highly correlated with height and shoot growth with correlation coefficients increasing with stand age. In each case, carbon and nitrogen at the 8-inch depth is more highly correlated with tree growth (30-40 percent) than values from 4- or 12-in depths (Figure 11b). Figure 11c suggests that increasing the number of positions per tree at which bulk density measures are taken from 4 to 8 increases correlation coefficients from about 10 percent to about 30 percent; it even appears that the simple correlation between bulk density and tree growth may reach 50 percent at plantation age of 3 years. Differences in correlation coefficients in Figure 11a and 11c between tree growth and A-horizon depth is due to differences in sample size; Figure 11a is based on the whole study area whereas Figure 11c is based on data from only one plot.

6. Multiple Regression Analyses:

1) The study area could not be stratified into areas which contained trees of similar height. However, an analysis was made to determine whether trees of a larger size class were associated with soils of a generally lower bulk density. Table 16 shows the characteristics of height and soil bulk density within six classes of tree height. The r^2 value for the relationship between mean tree height and soil bulk density for that height class was 0.39 indicating a weak association between the variables.

2) Using all 232 trees on the study area, an analysis was made to determine the extent to which variability in individual tree growth could be explained by the following variables:

TABLE 16: Height and soil density characteristics of six classes of tree height at Burntline.

Height Class (ft)	No. Trees	Mean Height (ft)	Mean Bulk Density (g/cc)
<1.6	-	-	-
1.6 - 3.2	3	2.95 ± 0.33	1.129 ± 0.063
3.2 - 4.9	8	4.20 ± 0.20	1.072 ± 0.033
4.9 - 6.6	43	6.04 ± 0.06	1.084 ± 0.015
6.6 - 8.2	112	7.48 ± 0.03	1.119 ± 0.010
8.2 - 9.8	58	8.89 ± 0.06	1.085 ± 0.012
>9.8	8	10.53 ± 0.16	1.028 ± 0.046

Mean soil bulk density	$\overline{D}$
A-horizon depth	$\overline{A}$
log (A-horizon depth)	log $\overline{A}$
shrub competition	Shrub
grass competition	Grass
visual evidence of compaction	K

The results of multiple regression analysis shown in Table 17 indicate that approximately 8-17 percent of the variability in tree growth was accounted for. The order of importance of variables was shrub competition, grass competition, and mean bulk density.

3) Eight positions of bulk density per tree

Similar to the situation reported for Foresthill, an evaluation was made as to whether doubling the sampling intensity of bulk density would increase the proportion of variability accounted for in measures of tree growth. Plot 2 was selected for this analysis as it had relatively uniform stocking, uniform shrub distribution, and a likelihood of a wide range in bulk density. The results of multiple regression analyses are shown in Table 18 and 19 which compare the results using eight positions of bulk density per tree with the two subgroups of four positions per tree. Similar to the analyses for Foresthill, Table 18 separates the measures of bulk density by depth, whereas Table 19 combines the data to provide one average measure of bulk density for each tree. The most important variable in accounting for variability in tree growth of Burntline commonly appears to be competition. The next most important is a measure of bulk density; either mean bulk density or, if the measures are kept separate, bulk density at the 8-in or 12-in depth

TABLE 17: Results of regression analysis of all 232 trees at Burntline study area showing the three most important variables accounting for variability in height, internode length, and diameter, together with their coefficients of determination (r^2).

	Independent Variables			r^2
Height at 7 yrs	-Shrub	-Grass	$-\bar{D}$	0.15
Internode 7	-Shrub	$+\bar{A}$	-Grass	0.08
DBH	-Shrub	-Grass	$-\bar{D}$	0.17

TABLE 18: Results of multiple regression analysis from Burntline (Plot 2, 25 trees) showing the relative importance of four and eight measures of bulk density per tree in accounting for variability in tree growth. Bulk density measures kept separate by depth.

Dependent Variable	Independent Variable			r^2
4 positions per tree: Group A				
Height at 7yr	-Shrub	$-D_8$	$+\bar{A}$	0.59
Height at 3yr	$-D_8$	-Shrub	$+\bar{A}$	0.47
DBH at 7yr	-Shrub	$+\bar{A}$	$-D_8$	0.58
4 positions per tree: Group B				
Height at 7yr	-Shrub	$+\bar{A}$	$-D_{12}$	0.51
Height at 3yr	$-D_{12}$	-Shrub	$+\bar{A}$	0.47
DBH at 7yr	-Shrub	$+\bar{A}$	$-D_{12}$	0.56
8 positions per tree				
Height at 7yr	-Shrub	$+\bar{A}$	$-D_8$	0.54
Height at 3yr	$-D_{12}$	-Shrub	$+\bar{A}$	0.45
DBH at 7yr	-Shrub	$+\bar{A}$	$-D_4$	0.57

TABLE 19: Results of multiple regression analysis from Burntline (Plot 2, 25 trees showing the relative importance of four and eight measures of bulk density per tree in accounting for variability in tree growth. Bulk density measures averaged over all depths.

Dependent Variable	Independent Variable			r^2
4 positions per tree: Group A				
Height at 7yr	-Shrub	$-\bar{D}$	$+\bar{A}$	0.56
Height at 3yr	-Shrub	$+\bar{A}$	$-\bar{D}$	0.45
DBH at 7yr	-Shrub	$+\bar{A}$	$-\bar{D}$	0.57
4 positions per tree: Group B				
Height at 7yr	-Shrub	$+\bar{A}$	$-\bar{D}$	0.52
Height at 3yr	$-\bar{D}$	-Shrub	+Grass	0.39
DBH at 7yr	-Shrub	$+\bar{A}$	$-\bar{D}$	0.56
8 positions per tree				
Height at 7yr	-Shrub	$+\bar{A}$	$-\bar{D}$	0.54
Height at 3yr	$-\bar{D}$	-Shrub	+Grass	0.43
DBH at 7yr	-Shrub	$+\bar{A}$	$-\bar{D}$	0.57

is more important than that at 4-in. The third most important variable appears to be A-horizon depth. No advantage can be seen to doubling the number of positions of bulk density measure from four to eight. The relatively high r^2 of 50 to 60 percent shows that, by chance, a small sample may account for a considerable portion of tree growth variability but, in general, such high coefficients should not be expected when using a larger sample.

4) An analysis was made of the extent to which variability in tree growth could be explained by adding variables quantifying the organic carbon content and mineralizable nitrogen. Variables used in this analysis were:

Mean bulk density	$\overline{D}$
bulk density at 4-in	D_4
bulk density at 8-in	D_8
bulk density at 12-in	D_{12}
visual estimate of compaction	K
A-horizon depth	$\overline{A}$
shrub competition	Shrub
grass competition	Grass
nitrogen at 4-in	N_4
nitrogen at 8-in	N_8
nitrogen at 12-in	N_{12}
mean nitrogen	$\overline{N}$
carbon at 4-in	C_4
carbon at 8-in	C_8
carbon at 12-in	C_{12}
mean organic carbon	$\overline{C}$

These variables were measured on the two tallest, the two shortest, and two intermediate-sized trees on each of the 10 plots. This provided a sample size of 60 trees.

Results of multiple regression analysis are shown in Table 20. It can be seen that the most important variables describing tree growth is the mean organic carbon content, followed by grass competition and mean nitrogen content. In each case, however, only 11 percent of the variability in tree growth could be accounted for. The unexpected negative coefficients associated with nitrogen content indicate possible interdependence of variables.

TABLE 20: Results of multiple regression analysis using the two largest, two smallest, and the two intermediate - sized trees per plot (60 trees) at Burntline, and adding variables measuring organic carbon and mineralizable nitrogen.

	Independent Variables			r^2
Height at 7 yr	$+\overline{C}$	-Grass	$-\overline{N}$	0.12
Internode 7	$+\overline{C}$	$-\log\overline{N}$	-Grass	0.11
DBH	$+\overline{C}$	-Grass	$-\overline{N}$	0.11

DISCUSSION

1. Within plantation variability in height and bulk density

The project was designed to determine the extent to which plantations can be stratified into significantly different classes of mean height and mean bulk density. Secondly, it was to be determined whether the height classes differed in terms of soil bulk density, and whether the bulk density classes differed in terms of mean tree height. The study at Foresthill, a 15-year-old plantation on an Aiken loam derived from andesites, showed that this kind of classification could be made and that the height classes did differ in bulk density, and that the bulk density classes supported trees of significantly different height. These results were not obtained on the 7-year-old Burntline plantation growing on a sandy loam Holland soil derived from granitic till. The plantation at Burntline appeared to be an intimate mixture of trees of different height and soil at different levels of bulk density. The range in bulk density on both plantations was, however, the same at 0.7 to 1.3 gm/cc.

2. Stand Growth

No inferences can be made regarding stand growth at Burntline because this plantation could not be stratified into area of different bulk density.

With regard to the Foresthill plantation, Table 21 shows that the 1.18 ac study area carried 358 trees per ac. The proportions of this area in bulk density classes 1 (high) through 4 (low) were 30, 18, 40 and 10 percent respectively. The volume per acre in each bulk density

TABLE 21: Summary of study area at Foresthill showing stand characteristics of stock and growth for each class of soil bulk density.

	Bulk Density Class				Burn Pile	Total
	1	2	3	4		
Area (ft^2)	15613	9114	20616	5380	925	51,648
Area (ac)	0.36	0.21	0.47	0.12	0.02	1.18
Area (%)	30	18	40	10	2	100
No. trees	78	75	215	50	4	422
No. trees/ac	216	357	457	416	200	358
Vol/tree (ft^3)	2.29	2.98	3.01	2.89		
Vol/ac (ft^3)	496	1064	1377	1204		
Vol/ac Reduction (% of bulk density Class 4)	-59	-12	+14	0		
Vol/tree Reduction (% of bulk density) Class 4)	-21	+3	+4	0		
Bulk Density (gm/cc)						
4 in	1.13	0.98	0.88	0.84		
6 in	1.14	0.99	0.90	0.83		
12 in	1.12	0.98	0.90	0.82		
Mean	1.12	0.98	0.90	0.83		

class was 496, 1064, 1377 and 1204 ft^3/ac respectively. Figure 13 illustrates these levels of volume by bulk density class together with corresponding data for average tree diameter and height.

Using the volume per acre on the area of lowest bulk density (class 4) as a standard, it can shown that the volume reduction on the area of highest bulk density was 59 percent. Similarly, volume per acre in bulk density class 2 was reduced by 12 percent, and that on bulk density class 3 was increased by 14 percent. Table 21 and Figure 13 show, however, that there is little real difference in mean tree volume in bulk density class 2,3 and 4, and that the reduction in mean tree volume in class 1, compared with that of bulk density class 4, is only 21 percent. Most of the reduction in productivity on the most compacted area was therefore due to lower survival. Using the number of trees per acre in bulk density class 4 as a standard, the reduction in stocking attributable to compaction was -48, -14, and +10% respectively for bulk density class 1, 2 and 3. Data presented in Table 21 and Figure 13 show greater tree growth in height, diameter, and volume at age 15 years in bulk density class 3 (0.9 gm/cc) than in bulk density class 4 (0.8 gm/cc). This could be interpreted as indicating that a small amount of compaction in the Aiken loam soil is favorable to growth. This interpretation is only reasonable if one includes the effect of the 1965/66 and 1966/67 drought on growth of trees on soils of different bulk density (Figs. 8, 9). In the absence of the drought it is reasonable to expect that the greatest tree growth would have occurred on the soils of lowest bulk density. It does appear from Table 21, however, that the slight increase in bulk density in class 3 may be at least partially responsible for the high survival. (An alternative reason for higher stocking in bulk density

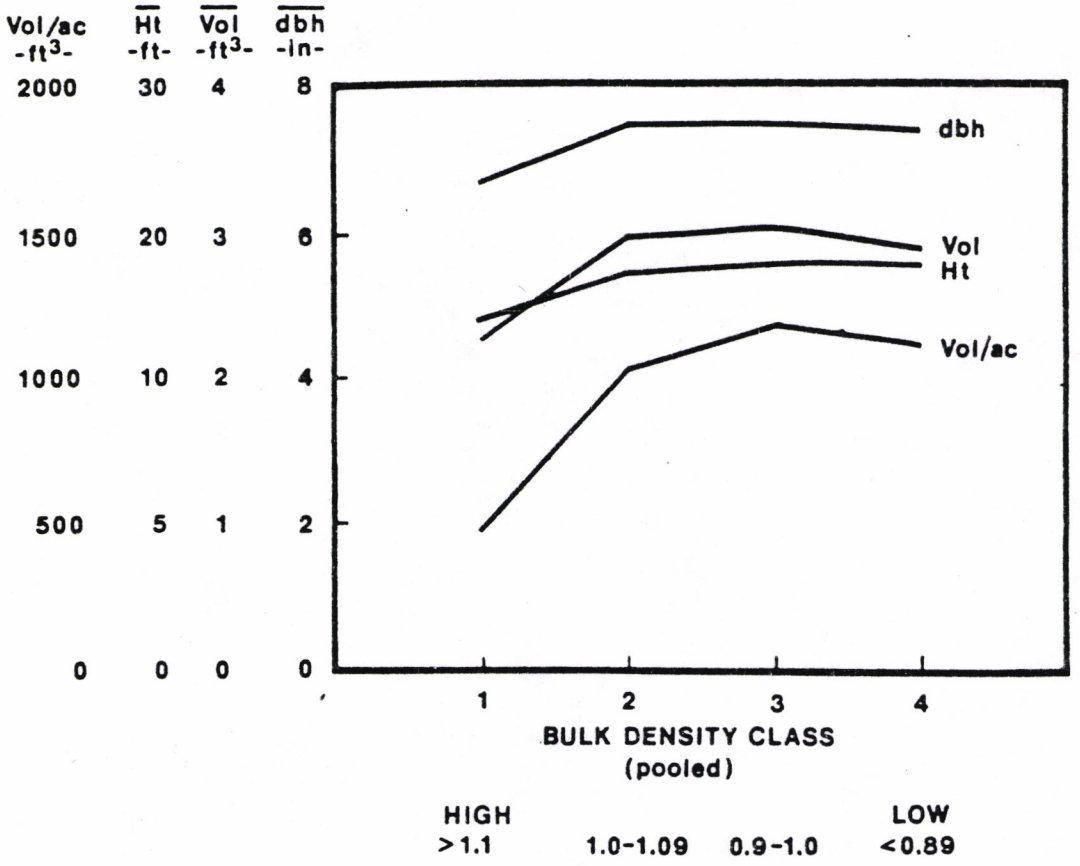

FIGURE 13: Stocking and growth characteristics on a stand basis for the portions of the study area at Foresthill with soils at different levels of bulk density.

class 3 compared with class 4 might simply be variability in actual planting density from the nominal 435/ac.)

CONCLUSIONS

1. Multiple regression analyses.

a. Foresthill

1) Bulk density ranged from 0.678 to 1.270 gm/cc with a mean of 0.946 ± 0.005 gm/cc. Soil bulk densities were distributed such that the study area could be stratified into areas with similar bulk density stocked with trees growing at similar growth rates.

2) For the study area as a whole, bulk density, A-horizon depth and competition from shrubs and surrounding trees account for only 10 to 20 percent of the variability in tree growth (Table 10, page 44).

3) Adding soil characteristics of organic carbon and mineralizable nitrogen which are associated with nutrition, increases the proportion of variability in tree growth that can be accounted for to about 40 percent (Table 11, page 47).

4) Using average values of bulk density, carbon, and nitrogen rather than measures separated by depth reduces the proportion of variability in tree growth accounted for to approximately 30 percent (Table 12, page 49).

5) Measuring soil bulk density at 8 positions around the tree rather than 4 appears to provide no real increase in ability to account for variability in tree growth.

6) In all analyses, current soil surface conditions were shown to account for somewhat more of the variability in tree growth a age 7 years than at the current age of 15 years.

7) Ranking locations around each tree from 1 to 3 in terms of visual evidence of soil compaction was very poorly related to measures

of soil bulk density. Regression coefficients for these two variables at both Foresthill and Burntline were $r^2 = 0.1$.

b. Burntline

1) Bulk density ranged from 0.781 to 1.378 gm/cc with a mean of 1.099 $\pm$ 0.006 gm/cc. Soil bulk densities were distributed such that the study area could not be stratified into areas of similar bulk density.

2) For the study area as a whole, only 8 to 17 percent of the variability in tree growth could be accounted for using the variables mean soil bulk density, A-horizon depth, and competition from shrubs and grasses. On Plot 2 (100 positions of bulk density within 20 x 20 m plot), 50-60 percent of the variability in tree growth was accounted for. The most important variables were shrub and grass competition.

3) The extent to which bulk density (compaction) can be shown to influence tree growth depends, in part, on the sample size. The detection of measurable effects also depends on the relationship between sampling intensity and variability in bulk density in the field.

4) Adding organic carbon and mineralizable nitrogen as variables did not increase the proportion of variability in tree height accounted for. Organic carbon did, however, become a more important variable than competition.

2. General Conclusions

The results of this study indicate that the following considerations can be raised with regard to forest management on Aiken loam soils at Foresthill:

1. Changes in soil bulk density attributable to harvesting and site preparation activities remain evident in the plantation 15 years after establishment.

2. Stratification of bulk density levels clearly defined the location of skid trails/haul roads, landings, and even spur skid trails 15 years after plantation establishment.

3. Height growth of trees on skid trails and landings is less than that on soils of lowest bulk density. At ages 1 and 2 years, reduction in annual shoot growth was 43 percent and at age 15 years the reduction was 13 percent. This indicates some recovery of growth in the compacted areas over time possible due to a combination of:

1) root growth and incorporation of organic matter ameliorating compaction.

2) root growth extending below, or beyond, the compacted area.

3) adequate root development within a compacted area.

However the continuance of relatively high bulk densities in the 4- to 12- inch surface layers has depressed height growth for at least 15 years.

4. Figure 14 compares the development of total height of trees on soils at Foresthill of the lowest and highest bulk density with curves drawn from data from Oliver and Powers (1978) of mean heights of ponderosa pine at 10 x 10 foot spacing at each site index. Although long term trends cannot be made with certainty, it appears that trees on bulk density class 1 (skid trails and landings) are currently growing at the equivalent of 20 site index points (one site index class) lower than trees on the remainder of the plantation. It is debatable whether this difference in growth will continue, in parallel fashion, resulting over

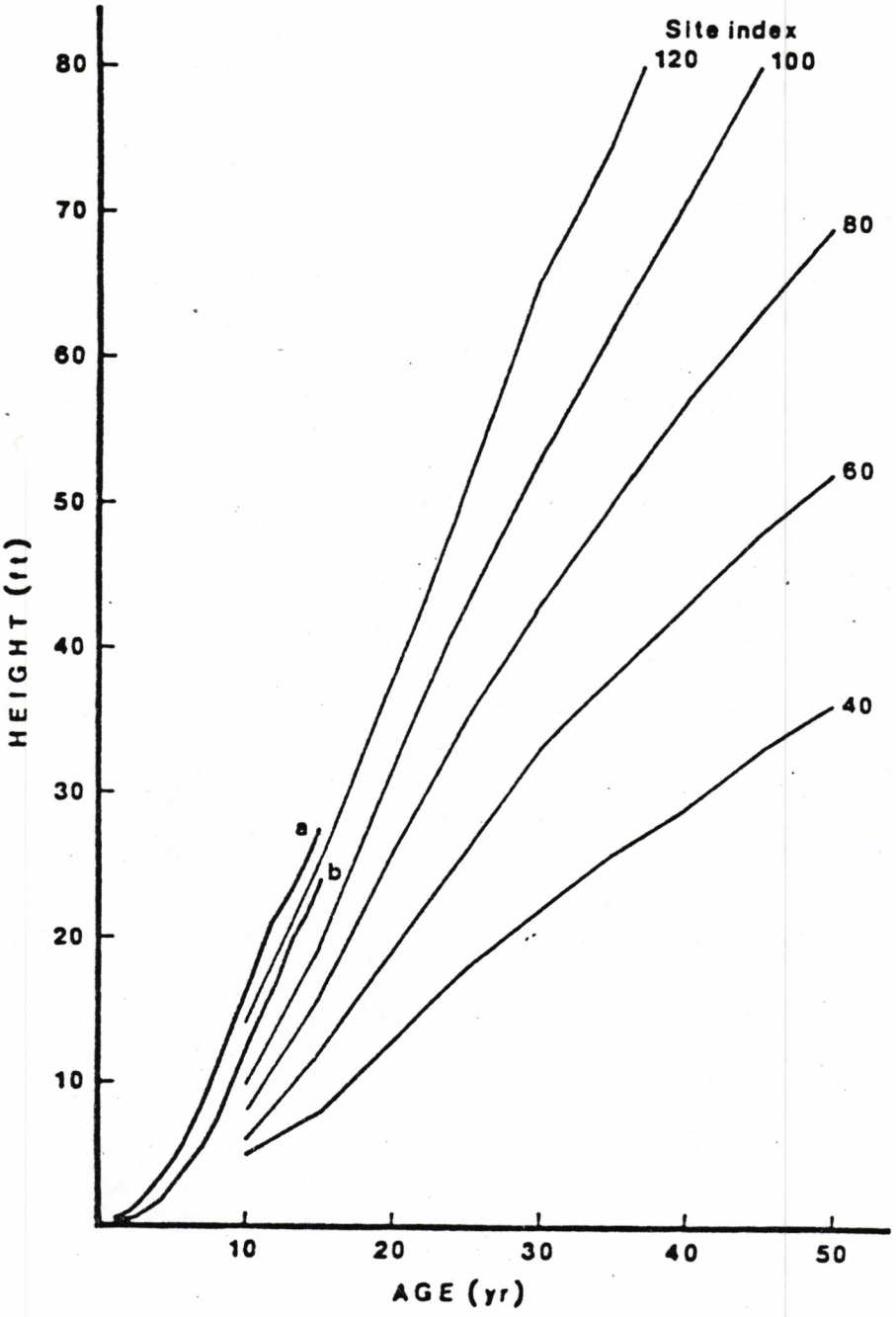

FIGURE 14: Height development of trees at Foresthill on soils of lowest (a) and highest (b) bulk density compared with curves drawn from data from Oliver and Powers (1978) of mean heights of ponderosa pine at 10 x 10 foot spacing at each site index.

a 50-year period with difference in productivity of about half a site index class. Alternatively, it could be argued that growth patterns may not remain parallel but that they will diverge in the manner of site index curves. The long-term projection of growth differences between the higher and lower bulk density classes may therefore be between one-half and one site index classes.

5. Volume production per acre on the area of highest bulk density (1.12 gm/cc) was 59 percent lower than on the area of lowest bulk density (0.83 gm/cc). Removing the effect of 48 percent lower survival on the most compacted area shows that reduction in volume due to soil compaction and associated disturbance alone was 21 percent.

6. Since the major difference in soil bulk density was in class 1, and that differences in tree growth and stand growth in classes 2,3 and 4 are statistically significant but relatively small, the forest manager's concern should concentrate on the proportion of land area covered by skid trails, haul roads, and landings. These areas should kept small but, if they are designated as permanent parts of the access system, compaction is of little consequence as they would not necessary be planted.

7. Given data from this study, projections can be made of the effects of allocating given proportions of the area to skid trails and landings. Calculations can be made of the expected loss in stand value corresponding to a given area resulting in soil bulk densities of >1.0 gm/cc. Costs could therefore be incurred in reducing skid trail and landing size to the point where the compounded costs equal the increased stand value obtained by the treatment.

8. If silvicultural prescriptions call for no intermediate

treatments throughout the rotation, and assuming that skid trails and landings will comprise a given proportion of land area, calculations can be made of the costs that can be incurred in ripping compacted areas in order to increase survival and growth to the level attained on the remainder of the plantation.

9. Although the study area could be stratified into four bulk density classes among which height growth was significantly different, multiple regression analysis showed that, in general, bulk density accounted for only 10-20 percent of the variability in height growth of individual trees.

10. Soil surface characteristics (bulk density, A-horizon depth, organic carbon, and mineralizable nitrogen) can account for about 1/3 the variation in tree height.

11. In areas of moderate to low bulk density, competition from grass and shrubs is more likely to influence growth of trees than differences in soil surface characteristics. In areas of high bulk density, soil characteristics can become the dominant factor influencing growth.

12. The marked difference in results from studies at Foresthill and Burntline indicate that care must be taken in making generalizations regarding the effects of compaction on growth of trees and stands. At Burntline, inability to stratify the study area into units of comparable bulk density or units of comparable height growth was due to the high degree of between-tree variability in bulk density and tree growth.

13. This study, involving 423 trees at Foresthill and 232 trees at Burntline, with bulk density measures at four positions and at three depths plus measures of organic carbon and mineralizable nitrogen, constitutes to most intensive study to date on within-plantation variability of tree growth and soil surface characteristics.

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Appendix A

THE TWO PROBE DENSIMETER

The Two Probe Densimeter or Campbell Pacific Nuclear Strata Gauge (Figure A1) is designed to measure soil bulk density nondestructively at successive 2-inch depths from the surface to 12 inches. The two extendible rods are 30.5cm apart. One rod contains ^{137}Cs which is a moderately high-energy source of gamma radiation. This rod can be drawn up into lead shielding in the body of the machine when not in use. The other rod contains a Geiger-Mueller detector tube which responds to gamma radiation passing through it by emitting pulses which are proportional to the amount of radiation received. The amount of radiation received follows the relationship:

$$I = I_o \, e^{-ux}$$

where: I = intensity of radiation at the detector

I_o = intensity of radiation at the source

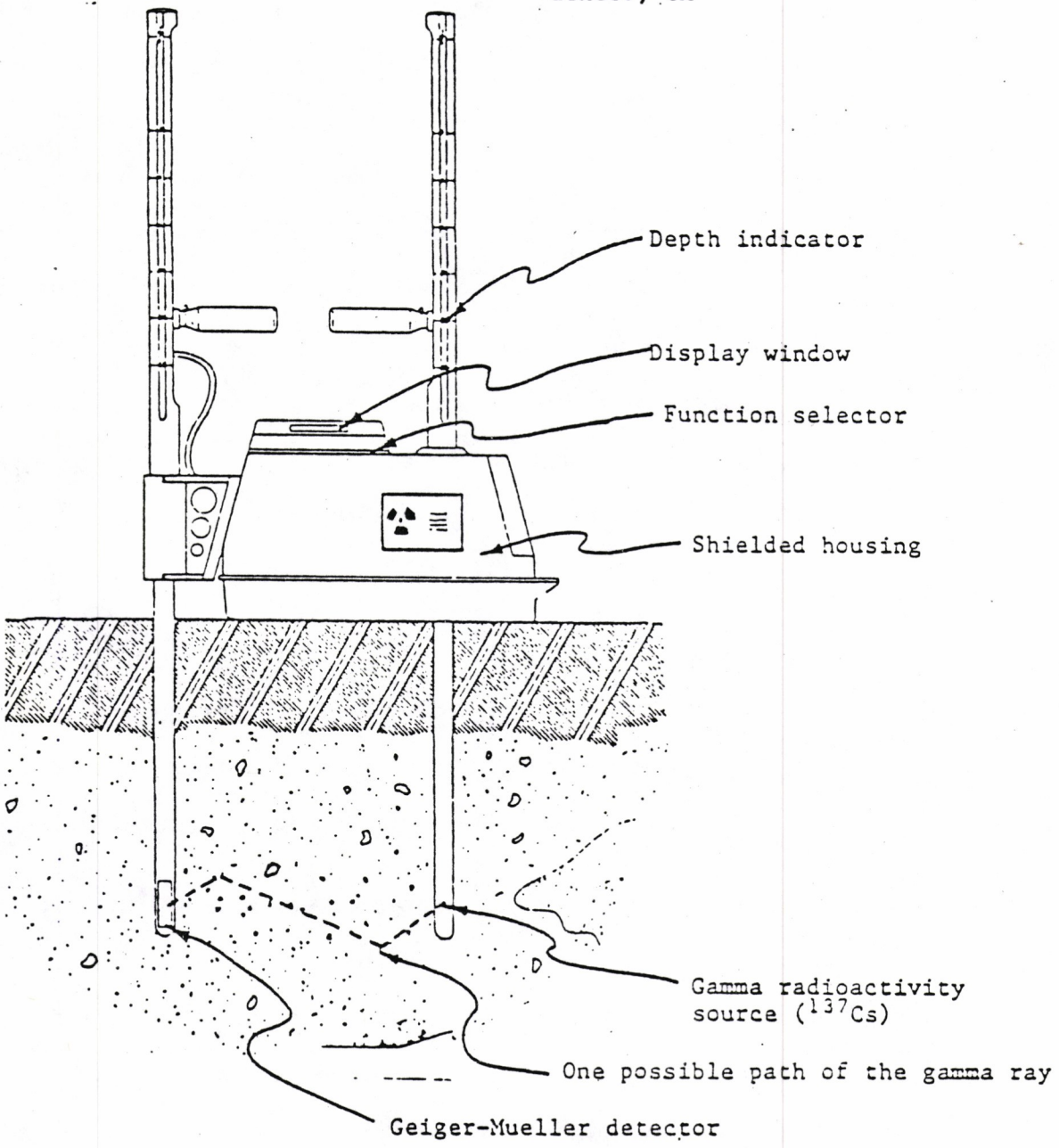
u = absorbtion coefficient of the measured substance

x = distance between the source and detector

The probe body contains an accurate electronic counter-timer which measures the time interval over which the pulses are counted. This count is a number which is inversely proportional to the density of the material through which the radiation passes. The time intervals available on the gauge are 0.25, 0.5, 1.0, and 2.0 minutes. The timer has a function that standardizes the count given for each interval to that of the 0.25min interval.

FIGURE A1: DOUBLE-PROBE NUCLEAR DENSIMETER

Stratagauge model
Mfc. by Campbell-Pacific Nuclear Corp.,
Pacheco, CA



Monitoring of Probe Performance

The performance of the probe is monitored by taking a count on a standard block three times a day. This standard count performs two functions: 1) ensures that the electronic components, i.e. the counter-timer, the detector tube, are functioning properly. 2) monitors the natural decrease in radiation intensity (I_o) over time due to the decay of ^{137}Cs. The half-life of ^{137}Cs is approximately 35 years therefore I_o can change measurably over the expected life of the machine. To correct potential errors due to decay of the energy source with time, the ratio of the count to the standard count is computed. This enables valid comparisons to be made of counts from different time periods.

Probe Calibration

Soil bulk density is the ratio between the dry weight of a sample and its volume. The relationship between count ratio and soil bulk density was determined by calibrating the probe using two aluminum boxes with volumes of 3.2 and 4.0 cu ft which were filled from approximately 600-700 lbs of soil collected from the Burntline study site. Thirty test soils were prepared in compaction boxes and approximately 400 data points were taken. Samples of this soil were used to measure soil moisture. The procedure for filling the calibration boxes is:

1) Soil from the 0-12 inch depth is dug and thoroughly mixed. It is then weighed out so as to create 2-inch layers or "lifts" in the box, such that a target bulk density is achieved. These lifts are poured in the box and tamped to

2-inch marks on the sides of the box. When the box is filled, the whole box is put on a large scale to check if the target density was achieved. If the actual density is within 0.02 g cm^{-3} of the target density, it is assumed the density throughout the box is acceptably uniform and the actual bulk density was recorded as the bulk density of the box.

2) When the soil can not be compacted down to a target density, it is wetted with small amounts of water, mixed and rolled in a large tarp allowed to stand overnight. Then step 1 is repeated.

3) Guide holes are driven into the soil using 5/8-inch steel pins and a steel guide plate. The probes are then inserted into the holes. At each depth of interest, four 2-minute interval counts are taken.

These procedures were followed to provide 22 calibration points covering a range in bulk density from 0.5 to 1.7g cm^{-3} for each of 3 depths and 2 probes.

Calibration Computations

The four 2-min counts taken at each depth in the calibration boxes were averaged to yield an average count which was divided by the standard count to give a count ratio. Least squares regression analysis was used to predict soil bulk density as a function of count ratio for each of the three depths to be measured in this study. Because two probes were to be used, six equations were generated, all of which had r^2 values >0.98 for the simple linear case. The linear

model was found to be an adequate expression of the exponential relationship $I = I_o e^{-ux}$ over the range of bulk densities between 0.5 - 1.7 gm/cc.

for probe CPN 2892:

4-inch depth: $P_t = 2.05737-0.20005(CR)$

8-inch depth: $P_t = 2.04368-0.18814(CR)$

12-inch depth: $P_t = 1.98805-0.18063(CR)$

for probe CPN 3856:

4-inch depth: $P_t = 2.07042-0.19995(CR)$

8-inch depth: $P_t = 2.05652-0.18587(CR)$

12-inch depth: $P_t = 2.00274-0.18153(CR)$

where: P_t = wet bulk density

CR = count ratio

Field Procedure

The procedure for determining the soil bulk density at each tree was:

1) The dripline of the crown of each tree was divided into four quadrants and a position for bulk density determination was selected subjectively in each quadrant (Figure A2). The guide plate was used to clear away the duff and surface rocks and to provide a smooth surface. The pins were then driven through the guide holes.

2) The pins and plate were removed and the probe was placed directly over the holes. The rod containing the source was extended its full length of 12-inches into one of the holes and the detector rod was then extended into the other hole.

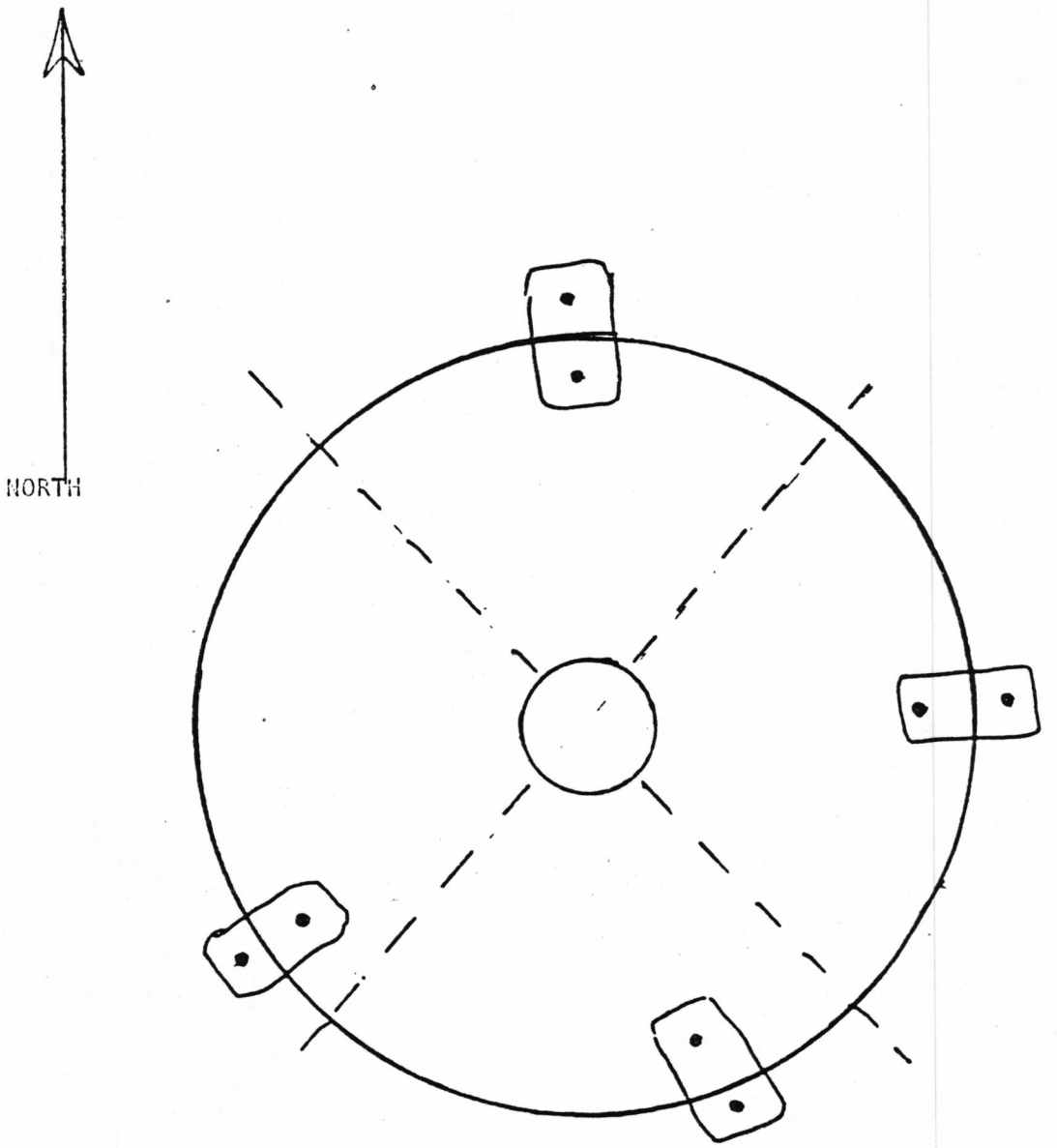


FIGURE A2: Diagram showing the position of the strataguage within four quadrants around the drop-line of tree crown.

3) Two 0.5 minute readings were taken at each depth (12-,8- and 4-in).

4) A 200-300g sample of soil was removed from each of the three depths for determination of gravimetric soil moisture content.

5) The depth of the A-horizon was measured in the auger hole by observing the depth at which the color of the soil was less than 3 or less using 10.0 YR Munsell color chart.

6) The soil was rated qualitatively on visual signs of compaction: 0=no compaction 1=compacted 2=very compacted. This was done primarily on the appearance of dense and platy structure in the upper 4-inch of soil around the auger hole.

Laboratory Procedures

Each soil sample from each quadrant and depth (12 separate samples per tree) was weighed, dried for at least 24 hr at 105 C in a forced air oven, and then weighed again to determine fractional moisture content:

$$w = (M_{wet} - M_{dry})/M_{dry}$$

where: w = fractional moisture content

M_{wet} = mass of the wet soil

M_{dry} = mass of the dry soil

Computations

The raw data: counts, standard count, soil wet weights and soil dry weights by quadrant and depth for each tree, were entered into a

computer data set. Programs were written to calculate count ratios and fractional moisture contents. Using the six regression equations developed, wet bulk densities were calculated. These were made comparable by adjusting them to dry bulk densities using the equation:

$$P_b = P_t/(1+w)$$

where: P_b = dry bulk density

P_t = wet bulk density

Appendix B

SOIL CHEMICAL ANALYSES

Sampling Procedure

A subsample of trees was chosen to assess the effect of available nitrogen and organic carbon content of the soil on tree growth. Trees with excessive brush competition and stem damage were eliminated from consideration in order to remove the confounding influences of these effects on tree growth. In each plot, the remaining trees were ranked by height and the two largest, the two median and the two smallest trees were chosen to sample for soil chemical analysis. Three 200 g samples were taken at Foresthill around the drip line of the tree crown at 0-4, and 8-12 inch depths. At Burntline, 4 samples were taken at the same 3 depths. The three samples at each depth were bulked for each depth separately to make a single sample per tree for each of the three depths. In the lab, each sample was air-dried, sieved to determine and remove the greater than 2mm fraction, and placed in marked cardboard "ice cream" containers.

Mineralizable Soil Nitrogen

Soil nitrogen available for plant growth was evaluated using the method of Powers (1980). Duplicate 5.0 g samples of thoroughly mixed soil from each of the three depths for each sampled tree were placed in test tubes (16 x 150 mm) containing 12.5 ml of distilled water. This was done to eliminate air pockets in the soil. The tubes were sealed with rubber stoppers and incubated for 14 days in the dark at 30 $\pm$ 1.5 C. Distilled water blanks were included to monitor

background NH_4^+ levels in the system. Following incubation, the tubes were shaken vigorously for 15 seconds and the contents transferred to a 100 ml distillation flask using three rinsings of 4N KCl totaling 12.5 ml. This displaced the NH_4^+ held by the cation exchange complexes into solution. Then 0.25 $\pm$ 0.05 g of carbonate free MgO was added to the flask. The flask was immediately attached to the steam distillation apparatus and steam-distilled until 25 ml of distillate was trapped in 5 ml of boric acid mixed-indicator solution. This process converts the NH_4^+ ions in solution in the distillation flask to NH_3 which is then carried over as a gas and condensed into the indicator solution. This distillate was then titrated with 0.01N HCl. Mineralizable N in ppm is calculated from the results of the titration corrected for background NH_4^+ in the distilled water blanks and adjusted for soil moisture content.

$$ppmN = [14000(N)(V_s-V_b)(1-MC)]/5$$

where: N = normality of the titrated acid

V_s = volume of acid titrated for sample

V_b = volume of acid titrated for blank

MC = moisture content of air dry soil expressed as a decimal

Soil Organic Carbon

Soil organic carbon was measured using the method of Walkley-Black (Black et al 1965). Oxidizable matter in the soil sample is oxidized by dicromate ion, $Cr_2O_7^{-2}$, facilitated by heat generated when two volumes of H_2SO_4 are mixed with one volume of 1N $K_2Cr_2O_7$. The $Cr_2O_7^{-2}$ that remains after oxidation of soil oxidizable matter is then determined by titration with standard $FeSO_4$ solution. The

difference between the total $Cr_2O_7^{-2}$ and what remains after oxidation is the amount of soil substances oxidized. Ferroin was used as the indicator in the titration. Duplicate samples of soils bracketing the range of organic carbon were run with both the combustion and oxidation techniques to test for recovery rates of soil carbon. This recovery rate is used to calculate a correction factor (f-value) for each depth. The amount of organic carbon determined by titration is then multiplied the f-value for each depth to give the total soil carbon content.

$$\text{Percent C} = [(E-(V_f N_f)(0.3))/M_s](f)$$

where: E = equivalents of $K_2Cr_2O_7$

V_f = volume of $FeSO_4$

N_f = normality of $FeSO_4$

(0.3) = grams per equivalent of carbon X 100

M_s = weight of oven dry soil

f = f-value (found to be 1.34)

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